Preliminary Hydrogeologic Assessment and Study Plan for a Regional Ground-Water Resource Investigation of the Blue Ridge and Piedmont Provinces of North Carolina

By Charles C. Daniel, III, and Paul R. Dahlen

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PREFACE

This report provides background information on two related topics—(1) the existing knowledge regarding the hydrogeologic framework of the complex heterogeneous fractured rock aquifer system that underlies the Blue Ridge and Piedmont of western North Carolina and (2) an outline of plans for a long-term study of ground-water conditions to advance current understanding of the resource in this region. Among the issues to be addressed are ambient ground-water quality on a regional scale, the potential for ground-water contamination, infiltration and recharge rates, the role of geologic structure in ground-water movement, time of travel between recharge and discharge areas, design of monitoring networks, implications for remediation, and policy development for ground-water management. The purpose of this report is to integrate information from basic research, field and laboratory experiments, and knowledge gained from hydrogeologic case studies in fractured-rock terranes to establish the basis for a long-term, multiyear study of ground water in the region. The report also provides information for nonspecialists about the potential of this fractured-rock terrane as a water source, and about regional ground-water-quality issues. The concept and design of a type-area site-selection process, its use in selecting sites for detailed studies of the ground-water resource, and characteristics of sites selected for the first phase of the study also are described.

The Blue Ridge and Piedmont physiographic provinces of western North Carolina cover 30,544 square miles in 65 counties. In 2000 the population of the region was approximately 6.11 million people. Of the total population, an estimated 1.97 million people, or 32.3 percent (based on the 1990 census), relied on ground water for a variety of uses, including commercial, industrial, and most importantly, potable supplies. Population in the region has grown substantially during the past 6 decades—in some counties the rate of growth has been greater than 1 percent per year. Ground-water use and the number of ground-water users has tended to parallel this growth in population.

In a region generally considered to have abundant water resources, summertime water rationing, water-quality degradation, and other problems have focused attention on the fact that there are limitations to the quantity and quality of available surface water. Consequently, ground water, which has been used principally for domestic supplies, is under consideration as a source for large public supplies or as a means to supplement available surface-water resources.

Ground water in the Blue Ridge and Piedmont Provinces traditionally has not been considered as a source for large supplies because of readily available and seemingly limitless surface-water supplies and the perception that ground water in the Blue Ridge and Piedmont Provinces occurs in a complex, generally heterogeneous geologic environment. Some reluctance to use ground water for large supplies is derived from the reputation of aquifers in these provinces for producing low yields to wells. Even with an increased understanding of the occurrence and movement of ground water in these fractured-rock terranes and with new skills and tools to aid in development and management of this resource, other issues fuel a continuing reluctance to explore the potential of these fractured-rock terranes as a public water source.

Concern about contaminated ground water is one such issue. As the population has grown, so has the number of real and potential sources of ground-water contamination. The same complex heterogeneous environment that thwarts ground-water development also hampers removal and remediation of contaminated water and aquifer materials. Concern about radon and other naturally occurring radionuclides in crystalline rock aquifers is another example.

Plans for the study described in this report were first developed in Raleigh, North Carolina, in 1999 as a result of a series of informal meetings between ground-water professionals from the Water Resources Discipline of the U.S. Geological Survey and the Groundwater Section of the North Carolina Division of Water Quality. The purpose of these meetings was to present information considered to be the state of knowledge about ground water in the Blue Ridge and Piedmont Provinces. It also was a goal of these meetings to identify what was not known and to speculate about emerging issues. An outline for these discussions was provided by the document, “Ground-Water Resources Evaluation Program,” written by the Ground-water Section staff in Raleigh. It became apparent during the course of these discussions that the participants believed that there were a sufficient number of issues to warrant an interdisciplinary investigation of ground water on a regional scale.

In planning the study, participants recognized that a number of issues regarding ground water in the Blue Ridge and Piedmont Provinces of North Carolina needed to be addressed, and that a study of this magnitude would require a willingness to dedicate resources and people to an effort that could span a decade or more. Study issues tended to fall into three general categories dealing with quality, quantity, and availability. Specifically, how much water is available? How can it be developed? What is its quality? What types of contamination have occurred and how is it being assessed and remediated? What are the safeguards to protect the resource and preserve it for future use? What are the long-term goals for management and utilization?

As with any resource, questions such as these can only be answered by a better understanding of the physical processes involved. If past research serves as an indicator of the future, not only will some questions be answered, but new questions will emerge, and new research and policy issues will be identified. We hope that this report will help scientists, managers, and the lay reader better understand the hydrogeologic system under investigation, the need for the study currently in progress, and initial steps taken to identify field sites for detailed research.

Charles C. Daniel, III

Paul R. Dahlen

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, TEMPERATURE, AND DEFINITIONS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
	Radioactivity	
picocurie per liter (pCi/L)	3.785	becquerel per liter

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Temperature: Temperature conversions between degrees Celsius (°C) and degrees Fahrenheit (°F) can be made by using the following equations:

$$°F = (1.8 \times °C) + 32$$
$$°C = 5/9\,(°F - 32)$$

Definitions:

µg/L	microgram per liter
mg/L	milligram per liter
+/-	plus or minus

Cover photographs: Research activities at the North Carolina State University Lake Wheeler Field Research Laboratory, Raleigh, North Carolina *(taken by Charles C. Daniel, III)*.

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By Charles C. Daniel, III,[1] and Paul R. Dahlen[2]

ABSTRACT

Prolonged drought, allocation of surface-water flow, and increased demands on ground-water supplies resulting from population growth are focuses for the need to evaluate ground-water resources in the Blue Ridge and Piedmont Provinces of North Carolina. Urbanization and certain aspects of agricultural production also have caused increased concerns about protecting the quality of ground water in this region.

More than 75 percent of the State's population resides in the Blue Ridge and Piedmont Provinces in an area that covers 30,544 square miles and 65 counties. Between 1940 and 2000, the population in the Piedmont and Blue Ridge Provinces increased from 2.66 to 6.11 million; most of this increase occurred in the Piedmont. Of the total population, an estimated 1.97 million people, or 32.3 percent (based on the 1990 census), relied on ground water for a variety of uses, including commercial, industrial, and most importantly, potable supplies.

Ground water in the Blue Ridge and Piedmont traditionally has not been considered as a source for large supplies, primarily because of readily available and seemingly limitless surface-water supplies, and the perception that ground water in the Blue Ridge and Piedmont Provinces occurs in a complex, generally heterogeneous geologic environment. Some reluctance to use ground water for large supplies derives from the reputation of aquifers in these provinces for producing low yields to wells, and the few high-yield wells that are drilled seem to be scattered in areas distant from where they are needed. Because the aquifers in these provinces are shallow, they also are susceptible to contamination by activities on the land surface.

In response to these issues, the North Carolina Legislature supported the creation of a Resource Evaluation Program to ensure the long-term availability, sustainability, and quality of ground water in the State. As part of the Resource Evaluation Program, the North Carolina Division of Water Quality, Groundwater Section, in cooperation with the U.S. Geological Survey, initiated a multiyear study of ground water in the Blue Ridge and Piedmont Provinces. The study began in 1999.

Most of the study area is underlain by a complex, two-part, regolith-fractured crystalline rock aquifer system. Thickness of the regolith throughout the study area is highly variable and ranges from 0 to more than 150 feet. The regolith consists of an unconsolidated or semiconsolidated mixture of clay and fragmental material ranging in grain size from silt to boulders. Because porosities range from 35 to 55 percent, the regolith provides the bulk of the water storage within the Blue Ridge and Piedmont ground-water system. At the base of the regolith is the transition zone where saprolite grades into unweathered bedrock. The transition zone has been identified as a potential conduit for rapid ground-water flow. If this is the case, the transition zone also may serve as a conduit for rapid movement of contaminants to nearby wells or to streams with channels that cut into

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or through the transition zone. How rapidly a contaminant moves through the system largely may be a function of the characteristics of the transition zone. The transition zone is one of several topics identified during the literature review and data synthesis, for which there is a deficiency in data and understanding of the processes involved in the movement of ground water to surface water.

Because the Blue Ridge and Piedmont study area is so large, and the hydrogeology diverse, it is not feasible to study all of the area in detail. A more feasible approach is to select areas that are most representative of the land use, geology, and hydrology to obtain an understanding of the hydrologic processes in the selected areas, and transfer the knowledge from these local "type areas" to similar regional hydrogeologic areas.

For the purpose of this study, the term "type area" applies to a 10- to 100-square mile area within a hydrogeologic terrane where information is sufficient to develop and test a concept of ground-water flow by using analytical or numerical methods that can be validated by field measurements. Ideally, these type areas are selected to be representative of the flow system that is present wherever a particular hydrogeologic terrane is present.

This report consists of two basic parts. The first part describes the results of a comprehensive review and synthesis of information and literature that provides the basic background for the study. This includes current (2002) knowledge regarding general geology and the hydrogeologic framework of the fractured-rock aquifer system that underlies the Blue Ridge and Piedmont Provinces. In spite of the quantity of information identified during the literature review and the amount of past work that has been documented, there are still research needs to be met.

The second part of the report describes State ground-water issues and problems, available data, and data deficiencies. It also describes the design and implementation of efforts to characterize ground-water quality and to quantify factors that influence the movement and availability of ground water in the hydrogeologic terranes characterized by (1) massive or foliated crystalline rocks overlain by thick regolith and (2) massive or foliated crystalline rocks overlain by thin regolith.

As of September 2001, seven sites had been identified as potential study sites to be used to characterize the hydrogeology and water quality of type areas considered representative of the larger terranes. Detailed geologic mapping, core drilling, well installation, and surface and borehole geophysical surveys are in progress at four of the sites.

INTRODUCTION

Historically, ground-water investigations in the Blue Ridge and Piedmont Provinces of North Carolina have received less emphasis than investigations of the more productive Coastal Plain aquifers. Coastal Plain aquifers supply water to most of that region's population, and these aquifers have received well-justified scientific attention. In contrast, the aquifers of the Blue Ridge and Piedmont serve only a small percentage of the municipal population because abundant rainfall and relief provide adequate surface-water resources. However, the small communities and rural population of the Blue Ridge and Piedmont Provinces are dependent upon ground-water supplies. Droughts, allocation of surface-water flow, contamination incidents, and increased demands on ground-water supplies have focused the need to evaluate ground-water resources in the Blue Ridge and Piedmont Provinces.

North Carolina has abundant water resources; however, ground-water characteristics in the regolith-bedrock aquifer system of the State are complex and poorly understood. More than 75 percent of the State's population resides in the Blue Ridge and Piedmont Provinces (North Carolina Department of Commerce, 1999), and the ground-water resources of this area of the State are important for supporting this large population.

The study area for ground-water investigations in the Blue Ridge and Piedmont Provinces of North Carolina is in the Appalachian Highlands of the eastern United States. The study area covers 30,544 square miles in western North Carolina. The geologic framework and hydrology of the study area are diverse and complex. Metamorphic and igneous rocks underlie most of the Blue Ridge and Piedmont, and regolith overlies these rock types. During 1990, 32.3 percent of the approximately 4.94 million people living within the 65 counties of the study area relied on ground water for potable supplies. Most of this water was supplied by wells at single-family homes. Ground water pumped from aquifers in the Piedmont supplied about 30 percent of the population within that province. However, ground water in the Blue Ridge Province supplied nearly 51.1 percent of the population. Well yields in sedimentary basins (principally the Deep River Triassic basin) in the Piedmont Province are among the lowest in the State.

The contribution to surface water by ground water from shallow aquifers commonly is overlooked, but it is an important component in watershed hydrology (Winter and others, 1998). About 46 percent of the annual discharge of Blue Ridge and Piedmont streams in the eastern United States originates as ground water (Rutledge and Mesko, 1996). The ground water carries not only naturally occurring dissolved constituents to the surface water but, in contaminated areas, also has the potential to carry contaminants to surface waters. Thus, understanding the ground-water system in the Blue Ridge and Piedmont Provinces is important not only to small communities and rural populations who depend on ground water for potable drinking water, but also to municipalities because of the potential for contaminated ground water to contaminate surface-water supplies.

Ground water in the Blue Ridge and Piedmont Provinces has been investigated in previous studies (Mundorff, 1948; LeGrand, 1967; Cederstrom, 1972, for example); however, the focus of these studies often was on ground-water quantity in the deeper bedrock aquifers. Relatively few studies have focused on shallow ground-water resources in the regolith, the ground-water contribution to streams (Rutledge and Mesko, 1996), or ground-water quality (Briel, 1997). Because of the relative lack of focus on shallow ground-water conditions in the Blue Ridge and Piedmont, there is a scarcity of information on shallow ground-water quality, movement, and storage.

The North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality, Groundwater Section (hereafter referred to as the Groundwater Section), has a mission to "promote the stewardship of North Carolina's ground-water resources for the protection of human health and the environment" (North Carolina Division of Water Quality, Groundwater Section, 1999). In order to fulfill this mission, the Groundwater Section needs to better understand the hydrogeology of the State's aquifers and the quality of water in these aquifers. Critical to this endeavor is understanding the movement of subsurface contaminants and(or) the movement of contaminants spilled at the land surface to supply wells or to surface-water bodies. The Groundwater Section has the goal of systematically developing hydrogeologic knowledge, widely distributing hydrogeologic data and interpretations, and providing the public with useful and meaningful information about North Carolina's near-surface aquifers (North Carolina Division of Water Quality, Groundwater Section, 1999).

As part of this mission, the Groundwater Section implemented a Resource Evaluation Program to evaluate ground-water resources across the State, with a focus on water quality. Given the natural division of the State into two major ground-water systems—with porous sedimentary aquifers beneath the Coastal Plain in the east and fractured crystalline bedrock beneath the Blue Ridge and Piedmont in the west—it was logical to evaluate these areas separately. A major effort is underway to review past ground-water studies in the Blue Ridge and Piedmont, develop plans for a long-term evaluation of ground-water resources in these provinces, and begin identifying and selecting study sites for research that will fill gaps in current knowledge. The study, which began in 1999, is being conducted cooperatively by the U.S. Geological Survey (USGS) and the Groundwater Section. The title of this cooperative study is "Ground-Water Resource Evaluation Program in the North Carolina Blue Ridge and Piedmont."

Principal objectives of the study are to (1) define the hydrogeologic framework of the Blue Ridge and Piedmont; (2) identify and characterize the hydrologic processes active in each province; (3) investigate the functioning of representative ground-water flow systems in the regolith-fractured rock aquifer systems by means of applied research, analytical methods, and computer simulation; (4) refine the present understanding of recharge and discharge processes and their role in determining ground- and surface-water quality; (5) estimate regional water budgets, including rates of natural discharge and recharge, changes in aquifer storage, and withdrawals; (6) determine the importance and interrelation of surface- and ground-water flow systems and their effects on water quality and potential for development; and (7) develop a comprehensive ground-water database for the region. This report is the first major information product resulting from the study and provides the hydrogeologic and organizational background for meeting the long-term objectives of the study. Results of this study, when combined with other studies in the Blue Ridge and Piedmont Provinces of North Carolina and the eastern United States, will help in the management of the Nation's water resources by defining the quality and quantity of these resources.

Purpose and Scope

The purpose of this report is to synthesize existing information about ground-water resources in the Blue Ridge and Piedmont Provinces of western North Carolina and to describe plans for quantifying the ground-water quality, hydrologic processes, and aquifer characteristics in these two physiographic provinces. The report has two basic parts.

The first part of the report describes the general geology and hydrogeology of the Blue Ridge and Piedmont study area. This includes current knowledge regarding the hydrogeologic framework of the complex heterogeneous fractured-rock aquifer system that underlies these physiographic provinces. Hydrogeologic terranes and conceptual flow systems within the study area are defined and described. A table of generalized hydrologic characteristics for each hydrogeologic terrane is provided for comparison of hydrogeologic terranes throughout the study area. Included in this discussion is background material describing certain fundamentals of ground-water hydrology to help the lay reader better understand the hydrologic characteristics of the aquifer system.

The second part of the report describes State ground-water issues and problems, available data and data deficiencies, and outlines the design of a long-term regional study of ground-water resources in a study area that covers 30,544 square miles and 65 counties in western North Carolina. Information from basic research, field and laboratory experiments, and knowledge gained from hydrogeologic case studies in fractured-rock terranes is used to establish the basis for a long-term, multiyear study of ground water in the region. The report describes the organization, and approaches for accomplishing the objectives of this regional ground-water study, which began in 1999, and is being conducted cooperatively by the USGS and the Groundwater Section. In addition, the report describes the criteria used to select sites for in-depth studies, site characterization procedures to be employed, and the characteristics of sites selected for the first phase of the study. Because field work began at several sites while this report was in preparation, short summaries of ongoing work at these sites are included. Information products, including databases, that are expected to be generated during the study also are described in the second part of the report.

Acknowledgments

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Description of the Study Area

North Carolina lies within three physiographic provinces of the southeastern United States (fig. 1): the Blue Ridge, the Piedmont, and the Coastal Plain (Fenneman, 1938). The Blue Ridge and Piedmont physiographic provinces encompass about 96,000 square miles (mi^2) and extend for about 1,000 miles (mi) from near New York City to near Montgomery, Alabama. The Piedmont Province is less than 40 mi wide in New Jersey, but is about 150 mi wide in North Carolina. The Blue Ridge Province extends southwestward from a very narrow section in southern Pennsylvania to northern Georgia; the province reaches its widest point in eastern Tennessee and western North Carolina, where it is nearly 100 mi wide. In North Carolina, the Blue Ridge and Piedmont Provinces encompass about 55 percent of the State, all or part of 65 counties, and cover 30,544 mi^2.

Physiography

In western North Carolina, the Blue Ridge Province contains the greatest mountain masses, highest altitudes, and the most rugged topography in eastern North America. The province is marked by steep, forest-covered slopes that are cut by numerous small stream valleys. More than 40 mountain peaks are greater than 6,000 feet (ft) in altitude, and another 82 peaks range between 5,000 and 6,000 ft in altitude (Conrad and others, 1975). The province is bounded on the west by the Ridge and Valley Province in Tennessee. On the east, the boundary between the Blue Ridge and the Piedmont is marked by the escarpment of the Blue Ridge front—a prominent topographic feature thought to be associated, in part, with faulting. The Blue Ridge front rises more than 1,700 ft above the Piedmont surface at the North Carolina-Virginia border and reaches a maximum relief of nearly 2,500 ft in central North Carolina.

The topography of the Piedmont Province consists of low, well-rounded hills and long, northeast-trending valleys and ridges. The surfaces of many ridge tops and interstream divides are relatively flat and are thought to be remnants of an ancient erosional surface of low relief. More recent erosion and downcutting by streams has dissected the Piedmont surface and created local topographic relief of 100 to 200 ft between interstream divides and stream bottoms. The Piedmont surface is 300 to 600 ft in altitude along the eastern border with the

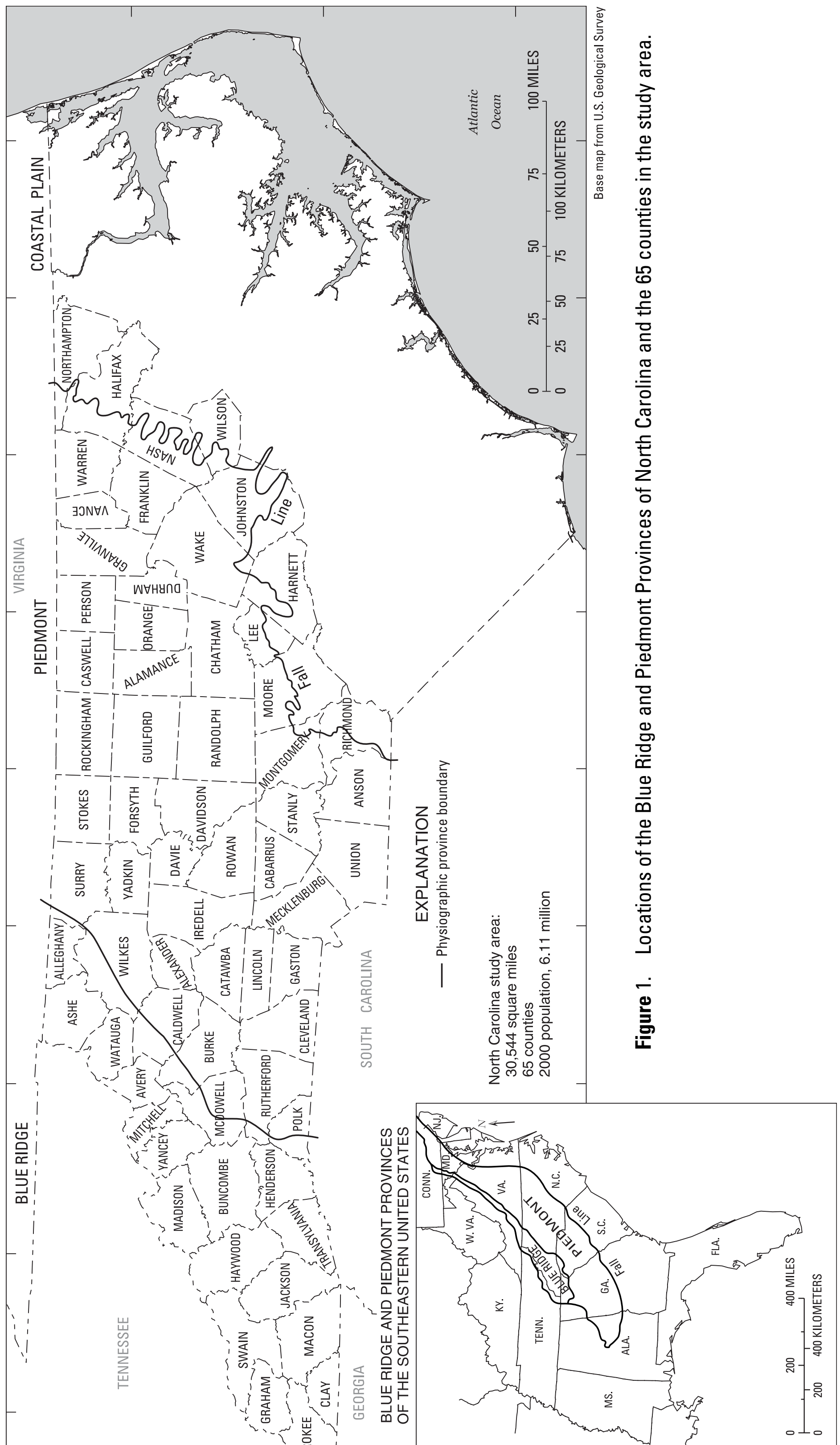


Figure 1. Locations of the Blue Ridge and Piedmont Provinces of North Carolina and the 65 counties in the study area.

Coastal Plain Province, and rises gradually to the west to about 1,500 ft in altitude at the foot of the Blue Ridge front.

Scattered across the undulating Piedmont surface are remnants of once higher mountains that, because of their resistance to erosion, stand as much as 500 to 1,600 ft above the local land surface. Some form prominent lines of hills. Others are isolated hills and mountains called monadnocks. Although more common in the western Piedmont, these elevated features are found throughout the province.

The Piedmont Province is bounded on the east by the Fall Line (fig. 1), which delineates the boundary between the hard, weathering-resistant crystalline rocks of the Piedmont and the less resistant sedimentary rocks of the Coastal Plain Province. At the Fall Line, the swift flowing streams of the Piedmont enter the Coastal Plain over a zone of rapids and low falls.

The Coastal Plain has little relief in contrast to the adjoining Piedmont. The Coastal Plain is marked by low-gradient streams flowing in broad valleys. The Coastal Plain is mostly composed of sand and clay units that thicken seaward from a feather edge at the Fall Line (fig. 1). Along the western edge of the Coastal Plain, the sediments are underlain at shallow depth by crystalline Piedmont rocks.

Precipitation

Precipitation within the study area ranges from a minimum of about 30 inches per year (in/yr) in the central Piedmont to a maximum in excess of 80 in/yr in southwestern North Carolina. Average (1951–80) precipitation in most areas is 40 to 50 in/yr (U.S. Geological Survey, 1986, p. 52). The area of maximum precipitation occurs in the Blue Ridge Province in northeastern Georgia, eastern Tennessee, and southwestern North Carolina as a result of orographic effects of the mountain ridges (Kopec and Clay, 1975).

Runoff

Average annual runoff (1951–80) ranges from a minimum of less than 10 inches (in.) to a maximum of about 50 in. The average runoff is 10 to 20 in/yr in most areas (U.S. Geological Survey, 1986, p. 52; Gebert and others, 1987). Runoff generally is higher in areas of the western Piedmont and Blue Ridge Provinces compared to the rest of the study area because of higher precipitation, steep hillslopes and streambed gradients, shorter growing seasons, lower temperatures, and lower evapotranspiration. During periods of low flow (usually September and October), most of the sustained nonregulated streamflow is from ground-water discharge.

Population Growth and Water Use

Population and industrial growth in the Blue Ridge and Piedmont Provinces of North Carolina have resulted in increased demands on water resources. Between 1940 and 2000, population in the Piedmont and Blue Ridge increased from 2.66 to 6.11 million; most of this increase occurred in the Piedmont (fig. 2). The number of people supplied by ground water between 1960 and 1980 also increased, although the percentage of the total population supplied by ground water remained fairly constant at 47 to 48 percent. Between 1980 and 1990, however, there was a 15.6 percent decrease in the population supplied by ground water. This decrease is attributed almost entirely to the high rate of population growth in four Piedmont counties (Forsyth, Guilford, Mecklenburg, and Wake; fig. 1) containing large urban areas (Winston-Salem, Greensboro, Charlotte, and Raleigh, respectively) that are supplied primarily by surface-water-based municipal supplies. Subtracting the populations of these four counties from the calculation results in a population of about 43 percent supplied by ground water in 1990. This percentage is closer to the previous 20-year trend. The decrease in the percentage of population supplied by ground water is important because of the implied increase in surface-water usage. Data for the number of people supplied by ground water in 2000 are not yet available; once the data are available, however, it will be possible to determine whether the decline in ground-water users in 1990 was a short-term fluctuation or the beginning of a long-term trend. If this new trend continues, surface-water resources may not be adequate to meet increased demands, and alternative water sources will be needed.

Currently (2002), most ground-water use is for domestic supplies. Dependence on ground-water supplies is not evenly divided between the two provinces. In 1990, about 30 percent of the population living within the Piedmont relied on ground water for potable supplies. In the Blue Ridge, ground water supplied 51.1 percent of the population (U.S. Bureau of the Census, 1992). Municipal and industrial water supplies in the two provinces are derived almost exclusively from surface-water sources. The potential for future development of surface water becomes limited, however, as the most suitable sites for reservoirs become inhabited or are used for other purposes, as land purchase and development costs increase, and as environmental concerns regarding surface-water impoundments cause delays in approval of necessary permits. In order to meet the increased demand for water, ground-water resources may need to be

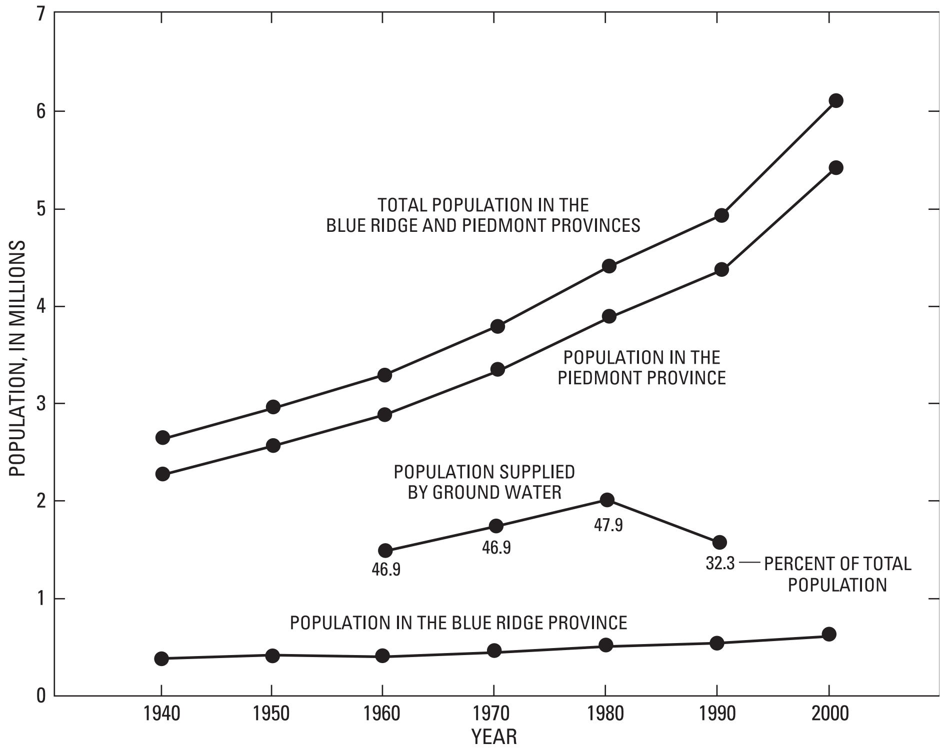


Figure 2. Growth in population and number of people supplied by ground water in the Blue Ridge and Piedmont Provinces of North Carolina, 1940–2000 (modified from Daniel, 1992a). Population data compiled from U.S. Bureau of the Census (1952, 1963, 1973, 1982, 1992) and U.S. Census Bureau (2001). Population supplied by ground water compiled from MacKichan and Kammerer (1961), North Carolina Division of State Budget and Management (1979, 1984), and U.S. Bureau of the Census (1992).

developed in the future to a much greater extent than in the past.

Previous Investigations

Between 1946 and 1971, reconnaissance ground-water-resource investigations were completed for 14 areas that encompassed all 65 counties in the Blue Ridge and Piedmont Provinces of North Carolina (fig. 3). The results of these studies are contained in the published reports cited in figure 3. Included in the reports are maps that show well locations in each county and tables of well records that provide details of well construction, yield, use, topographic setting, water-bearing formations, and miscellaneous notes. Data were compiled from these reports for drilled wells completed in bedrock and statistically analyzed by Daniel (1989) to determine relations between well yield and construction, topographic setting, hydrogeologic units, lithotectonic belts, and other characteristics. A hydrogeologic unit map of the Blue Ridge and Piedmont Provinces of North Carolina also was compiled by Daniel and Payne (1990) as part of this work.

The hydrogeology of the Blue Ridge and Piedmont Provinces of the eastern and southeastern United States is described by LeGrand (1967), Heath (1984), and Swain and others (1991). A book dealing with various ground-water-related topics ranging from availability to quality in the Piedmont of the eastern United States was compiled by Daniel and others (1992). The hydrology of the Valley and Ridge, Blue Ridge, and Piedmont Provinces, extending from Pennsylvania to Alabama, was studied as part of the USGS's Regional Aquifer-System Analysis (RASA) Program; this study, known as the Appalachian Valleys-Piedmont RASA, resulted in the production of numerous reports that are listed in a bibliography compiled by Sun and others (1997). The hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, Blue Ridge, and Piedmont were investigated by Rutledge and Mesko (1996).

The hydrogeologic framework of the Piedmont of North Carolina was described by Harned (1989) as part of a reconnaissance study of ground-water quality. Details of the hydrogeologic framework, particularly the nature of

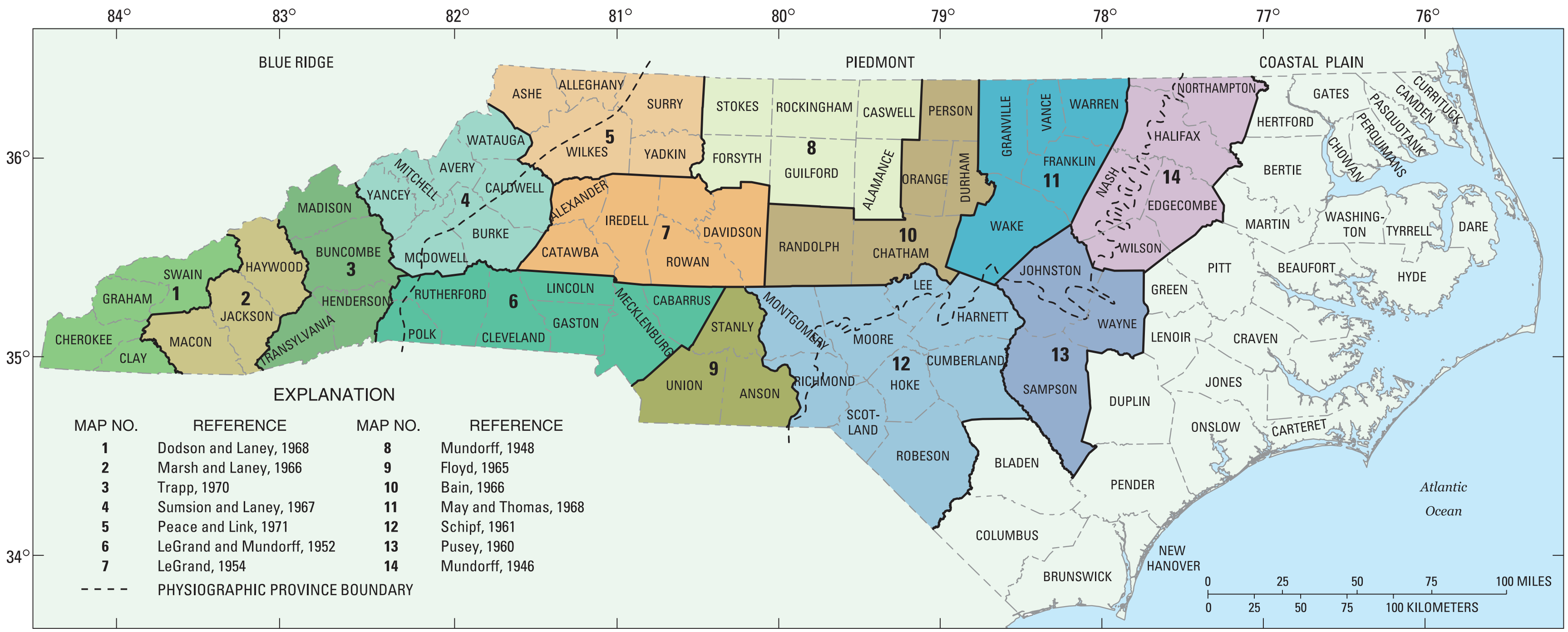


Figure 3. Study areas of previous reconnaissance ground-water investigations that are sources of well data for the Ground-Water Resource Evaluation Program in the North Carolina Blue Ridge and Piedmont.

the transition zone between bedrock and regolith, were refined by Harned and Daniel (1992). Ground-water recharge rates for selected sites in the Blue Ridge and Piedmont of North Carolina have been estimated by Daniel and Sharpless (1983), Harned and Daniel (1987), and Daniel (1990a, b). Detailed studies of ground-water recharge in the central Piedmont have been made by Daniel (1996), Mew and others (1996), and Daniel and Harned (1998). The distribution of fracture permeability with depth in fractured bedrock beneath different topographic settings in the Piedmont of North Carolina has been statistically characterized by Daniel (1992b) and Daniel and others (1997). The nature of the relation between well yield and topographic setting has been further investigated by McKelvey (1994), Ali (1998), and Daniel and Ali (1999); these authors found a relation between well yields and subdivisions of topographic settings based on drainage patterns and the implied presence or absence of bedrock fracturing.

HYDROGEOLOGIC SETTING

The geology of the Blue Ridge and Piedmont Provinces is complex; the hydrogeology of these physiographic provinces is equally complex. All major classes of rocks—metamorphic, igneous, and sedimentary—are present, although metamorphic rocks are the most abundant. The metamorphic and igneous rocks range in composition from felsic to ultramafic and in age from Precambrian in the Blue Ridge to Triassic and Jurassic in the Piedmont. Three or more periods of igneous intrusion (Fullagar, 1971) have resulted in the emplacement of plutonic bodies that range in size from batholiths down to dikes, sills, and veins. Most intrusions have been metamorphosed, deformed, and fractured, but some are massive and have little or no foliation. The degree of metamorphism of the rocks varies from low rank to high rank. Many have been folded and refolded during multiple metamorphic and orogenic events. Within the crystalline rocks of the Piedmont are down-faulted basins (grabens) filled with sedimentary rocks of Triassic age.

The rocks are broken and displaced by numerous faults and zones of shearing, some of which are many miles in length. Rock fractures without displacement, called joints, are ubiquitous. The joints commonly cluster in groups oriented generally in one or more preferred directions. All rocks have been subjected to uplift, weathering, and erosion, which have resulted in the widening of fractures and the formation of new openings, such as stress-relief fractures. These breaks in the otherwise solid rock are the conduits through which ground water flows in the bedrock.

Bedding and planes of metamorphic foliation generally are folded and tilted and can have almost any attitude and orientation. Fractures, bedding, and foliation create heterogeneities in the rocks and result in permeability that typically is greatest parallel to bedding, foliation, and zones of fracture concentration; permeability typically is least at right angles to the plane of these features.

Bedrock may be exposed at land surface on steep slopes, rugged hilltops, or in stream valleys, but nearly everywhere else it is overlain by unconsolidated material that may reach depths greater than 100 ft. Collectively this unconsolidated material, which is composed of saprolite, alluvium, and soil, is referred to as regolith. Saprolite is clay-rich, residual material derived from the in-place weathering of bedrock. When the bedrock weathers to form saprolite, the relict structures generally are retained, and the directional properties of permeability also are retained. In many valleys, the saprolite has been removed by erosion and the bedrock is exposed or thinly covered by alluvial deposits. Soil is present nearly everywhere as a thin mantle covering both the saprolite and alluvium. The water-storing and transmitting characteristics of bedrock and regolith, and the hydrologic relation between them, is a major factor in the water-supply potential of the ground-water system in the Blue Ridge and Piedmont Provinces.

Crystalline Rock

Metamorphic and igneous crystalline rocks underlie most of the Blue Ridge and Piedmont. Metamorphic and igneous rocks in these provinces range in composition from felsic to ultramafic and range in age from Middle Proterozoic for granitic rocks in the Blue Ridge (Tilton and others, 1960) to Triassic-Jurassic for the unmetamorphosed dikes and sills of mafic composition that intrude older Piedmont rocks (Weigand and Ragland, 1970; Ragland and others, 1983). Rocks that crop out in the Piedmont underlie parts of the Atlantic Coastal Plain at depth.

Bedding and foliation within metamorphic bedrock usually are folded and tilted, can exhibit variable orientations, and commonly intersect one another in systematic geometric patterns. Bedrock generally is weathered to saprolite; however, relict structures and directional properties controlling permeability or hydraulic conductivity are retained in places. Although most rocks in the area have been metamorphosed and have strong directional fabrics, igneous intrusives emplaced after the last metamorphic event in the late Paleozoic tend to be less foliated and less fractured. Most of the rocks were subjected to uplift during the Cenozoic Era and subsequent weathering and erosion, which opened or widened existing fractures and created new ones by stress relief. Fault zones of different types, scales, and orientations are common; some are characterized by an extensive and intricate network of fractures.

Ground-water flow within metamorphosed carbonate rocks of the Blue Ridge and Piedmont Provinces can be substantial. Most of the reported areas of high well yields, however, are outside of North Carolina (Causey, 1965; McGreevy and Sloto, 1976, 1977). Metamorphosed carbonate rocks in North Carolina are limited almost exclusively to the Murphy and Blue Ridge belts in the Blue Ridge physiographic province. The most prominent occurrence in the Murphy belt is the Murphy Marble; in the Blue Ridge belt, the most extensive exposures of carbonate rock are found in the vicinity of the Grandfather Mountain window where the Shady Dolomite is exposed beneath the Linville Falls fault (Bryant and Reed, 1970). Linville Caverns, which were formed by dissolution of the Shady Dolomite, lie in the southwestern part of the window. According to Daniel (1989), the rocks of the Murphy belt were the source of the highest average well yield (25.5 gallons per minute [gal/min]) of the 14 belts that were evaluated. In contrast, the lowest average well yields were from noncarbonate crystalline rocks in the Smith River allochthon and noncarbonate sedimentary rocks in the Triassic basins; both belts provide an average yield of about 11.5 gal/min. The high yields in the Murphy belt may be a result of several factors, including the presence of solution openings in the carbonate rocks and high recharge rates associated with abundant precipitation in southwestern North Carolina. Large bodies of metamorphosed carbonate rocks are not found in the North Carolina Piedmont, although some small carbonate (marble) bodies have been mapped in the Inner Piedmont and Kings Mountain belts (Goldsmith and others, 1988).

Sedimentary Rock

Several sedimentary basins within the Piedmont Province of North Carolina contain rocks of early Mesozoic age (fig. 4). These basins are part of a series of elongated, down-faulted basins that crop out in a discontinuous belt almost 1,500 mi long extending from northeastern Nova Scotia to South Carolina. The Mesozoic basins in North Carolina are the Deep River, Danville, and Davie County basins (fig. 4). The largest basin in North Carolina is the Deep River basin, which is bordered on its eastern margin by the Jonesboro fault. Based on physiography, structure, and lithology, the Deep River basin is divisible into three subbasins, the Durham, Sanford and Wadesboro, which are named for the largest city in each subbasin (Reinemund, 1955). The total thickness of Triassic sedimentary rocks in the Deep River basin ranges from 7,000 to 10,000 ft.

These basins were formed in Triassic and Jurassic times during the incipient rifting of the continents that formed the Atlantic Ocean. Concurrently, they filled with thick sequences of continental sediment eroded from surrounding crystalline highlands. These rift-basin sedimentary rocks primarily consist of interbedded red shale, sandstone, and siltstone. Locally, conglomerate and lacustrine black mudstone are common, and coal is present in the Richmond, Va., Danville, and Deep River basins of North Carolina (fig. 4). Interbedded basaltic lava flows have been identified in some basins (Froelich and Olsen, 1985).

Most geologic formations within the early Mesozoic basins strike northeast and dip from 5 to 40 degrees toward the main border fault; dips are commonly toward the northwest or southeast. These Mesozoic deposits lie unconformably on Precambrian and Paleozoic crystalline rocks. Intrusive dikes and sills predominantly composed of diabase are common in and adjacent to the early Mesozoic basins (Ragland, 1991).

Hydrogeologic Units

Within the Blue Ridge and Piedmont of North Carolina are hundreds of rock units that have been defined and named by various conventions in keeping with classical geologic nomenclature. The geologic nomenclature, however, does little to reflect the water-bearing potential of the different units. To overcome this shortcoming and to reduce the number of rock units to the minimum necessary to reflect the differences in water-bearing potential, a classification scheme based on origin, composition, and texture was devised (table 1). The classification of hydrogeologic units shown in table 1 reflects not only the primary porosity of rocks but also the potential of the rocks for developing secondary porosity in the form of fractures and solution openings. Composition and texture also reflect, in part, the rate and depth of weathering of these rock units and the water-bearing properties of the resulting regolith.

The origin of the hydrogeologic units in table 1 is indicated by the rock class (igneous, metamorphic, or sedimentary) or subclass (metaigneous, metavolcanic, or metasedimentary). The composition of the igneous, metaigneous, and metavolcanic rocks is designated as

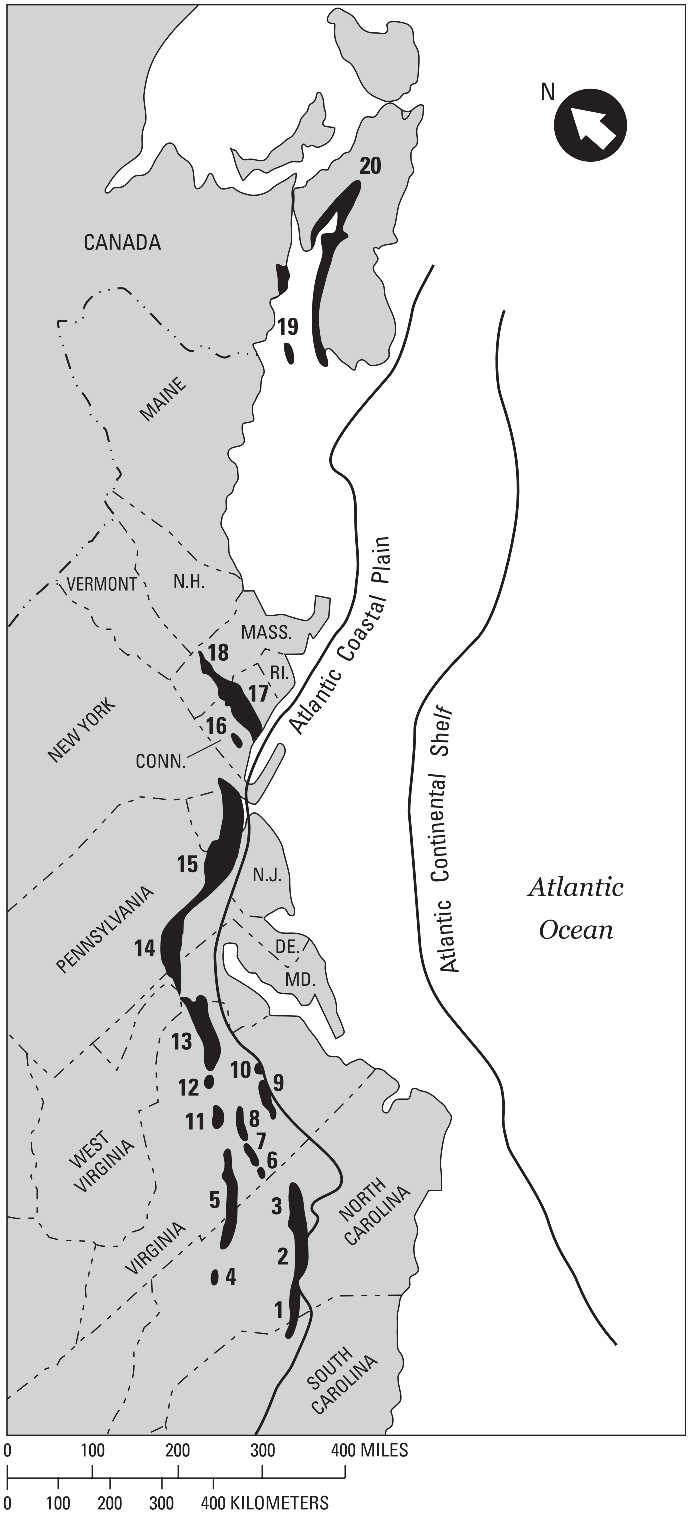


Figure 4. Exposed early Mesozoic basins in eastern North America (from Smoot and Robinson, 1988, fig. 1).

Table 1. Classification and lithologic description of hydrogeologic units in the Blue Ridge and Piedmont Provinces of North Carolina

[From Daniel, 1989]

Symbol	Hydrogeologic unit	Lithologic description
		IGNEOUS INTRUSIVE ROCKS
IFI	Igneous, felsic intrusive	Light-colored, mostly granitic rocks, fine- to coarse-grained, some porphyritic, usually massive, locally foliated; includes granite, granodiorite, quartz diorite, quartz monzonite, alaskites.
III	Igneous, intermediate intrusive	Gray to greenish-gray, medium- to coarse-grained, massive rocks of dioritic composition; includes assemblages of closely associated diorite and gabbro where they are too closely associated to be mapped separately.
IMI	Igneous, mafic intrusive	Dark greenish-gray to black, medium- to coarse-grained intrusive bodies; primarily gabbroic in composition, includes closely associated gabbro and diorite where they are too closely associated to be mapped separately, ultramafic rocks, diabase, dunite.
		METAMORPHIC ROCKS
		Metaigneous Rocks (Intrusive)
MIF	Metaigneous, felsic	Light-colored, massive to foliated metamorphosed bodies of varying assemblages of felsic intrusive rock types; local shearing and jointing are common.
MII	Metaigneous, intermediate	Gray to greenish-gray, medium- to coarse-grained, massive to foliated, well-jointed, metamorphosed bodies of dioritic composition.
MIM	Metaigneous, mafic	Massive to schistose greenstone, amphibolite, metagabbro and metadiabase, may be strongly sheared and recrystallized; metamorphosed ultramafic bodies are often strongly foliated, altered to serpentine, talc, chlorite-tremolite schist and gneiss.
		Metavolcanic Rocks (Extrusive-Eruptive)
MVF	Metavolcanic, felsic	Chiefly dense, fine-grained, light-colored to greenish-gray felsic tuffs and felsic crystal tuffs, includes interbedded felsic flows. Felsic lithic tuffs, tuff breccias, and some epiclastic rocks; recrystallized fine-grained groundmass contains feldspar, sericite, chlorite, and quartz. Often with well-developed cleavage, may be locally sheared; phyllitic zones are common throughout the Carolina slate belt.
MVI	Metavolcanic, intermediate	Gray to dark grayish-green tuffs and crystal tuffs generally of andesitic composition; most with well-developed cleavage; also includes interbedded lithic tuffs and flows of probable andesitic and basaltic composition and minor felsic volcanic rocks.
MVM	Metavolcanic, mafic	Grayish-green to dark-green, fine- to medium-grained andesitic to basaltic tuffs, crystal tuffs, crystal-lithic tuffs, tuff breccias and flows; pyroclastic varieties may contain lithic fragments; commonly exhibits prominent cleavage; alteration minerals include chlorite, epidote, calcite, and tremolite-actinolite.
MVE	Metavolcanic, epiclastic	Primarily coarse sediments including interbedded graywackes and arkoses and minor conglomerates, interbedded argillites and felsic volcanic rocks; much of the sequence is probably subaqueous in origin and most of the rocks were derived from volcanic terranes.
MVU	Metavolcanic, undifferentiated	Volcanic rocks of all origins (extrusive and eruptive) and compositions (felsic to mafic) interbedded in such a complex assemblage that mapping of individual units is not practical.
		Metasedimentary Rocks
ARG	Argillite	Fine-grained, thinly laminated rock having prominent bedding plane and axial plane cleavage; locally includes beds of mudstone, shale, thinly laminated silt-stone, conglomerate, and felsic volcanic rock.
GNF	Gneiss, felsic	Mainly granitic gneiss; light-colored to gray, fine- to coarse-grained rocks, usually with distinct layering and foliation, often interlayered with mafic gneisses and schists.
GNM	Gneiss, mafic	Mainly biotite hornblende gneiss; fine- to coarse-grained, dark gray to green to black rock, commonly with distinct layering and foliation, often interlayered with biotite and hornblende gneisses and schists, and amphibolite layers at some places.
MBL	Marble	Fine- to medium-grained, recrystallized limestone and dolostone; found primarily in the Murphy belt.
PHL	Phyllite	Light-gray to greenish-gray to white, fine-grained rock having well-developed cleavage; composed primarily of sericite but may contain chlorite; phyllitic zones are common throughout the Carolina slate belt and probably represent zones of shearing, although displacement of units is usually not recognizable.

Table 1. Classification and lithologic description of hydrogeologic units in the Blue Ridge and Piedmont Provinces of North Carolina (Continued)

[From Daniel, 1989]

Symbol	Hydrogeologic unit	Lithologic description
QTZ	Quartzite	Metasandstone, often feldspathic to highly feldspathic, thin- to thick-bedded with graded bedding at some places, includes meta-arkose and metaconglomerate; often interbedded with mica schist, phyllite, and slate.
SCH	Schist	Schistose rocks containing primarily the micas muscovite or biotite or both, occasional sericite and chlorite schists; locally interlayered with hornblende gneiss and schist, commonly with distinct layering and foliation.
SLT	Slate	Fine-grained metamorphic rock formed from such rocks as shale and volcanic ash, possesses the property to part along planes independent of the original bedding (slaty cleavage).
	MISCELLANEOUS	
TRI	Triassic sedimentary rocks	Mainly red beds, composed of shale, sandstone, arkose, and conglomerate (fanglomerate near basin margins).
CPL	Coastal Plain basement	Undifferentiated crystalline basement rocks of igneous and metamorphic origin overlain unconformably by sedimentary sands, gravels, clays, and marine deposits.

felsic, intermediate, or mafic except for the addition in the metavolcanic group of epiclastic rocks and compositionally undifferentiated rocks. These two groups were added to the metavolcanic group because they represent significant areas of metavolcanic rocks with distinct characteristics. The epiclastic rocks are the result of volcaniclastic deposits being reworked by sedimentary processes that included sufficient admixture of terrigenous sediment during deposition to make the rocks texturally distinct. The areas mapped as compositionally undifferentiated rocks contain complex and small-scale stratigraphic changes that make differentiation of separate units impractical. Composition also is shown in the metasedimentary units of gneiss, marble, and quartzite. The other metasediments are designated primarily on the basis of texture (grain size, degree of metamorphism, and development of foliation).

Two miscellaneous classifications account for the sedimentary rocks within the Triassic basins and the undifferentiated crystalline basement rocks east of the Fall Line that are overlain unconformably by sediments of Cretaceous age and younger.

By using the classification scheme in table 1 and the most recent geologic maps available, Daniel and Payne (1990) compiled a hydrogeologic unit map for the Blue Ridge and Piedmont Provinces in North Carolina (fig. 5). The percentage of the study area underlain by each hydrogeologic unit is given in table 2. Well-location maps were superimposed on the hydrogeologic unit map, and the units corresponding to the well locations were coded and entered into a computerized data file for analysis to determine the well yields in each unit (Daniel, 1989). The relation between well yield and hydrogeologic unit identified by Daniel (1989) is shown in figure 6.

Table 2. Relative percentages of hydrogeologic units in the Blue Ridge and Piedmont Provinces of North Carolina

Hydrogeologic unit[a]	Percent
GNF	22
GNM	18
MIF	9.9
QTZ	7.3
ARG	6.4
MVF	6.3
IFI	5.4
SCH	5.2
TRI	5.1
MII	3.1
MVU	3.0
MIM	1.9
MVE	1.9
PHL	1.7
SLT	0.8
IMI	0.7
MVM	0.6
MVI	0.5
III	0.1
MBL	0.1

[a] Hydrogeologic units are named and described in table 1.

Additional analyses were made by Daniel (1989) to determine the relation between well yield, and other well characteristics, and topographic setting. These data also have been used to determine the average saturated thickness of regolith associated with each hydrogeologic

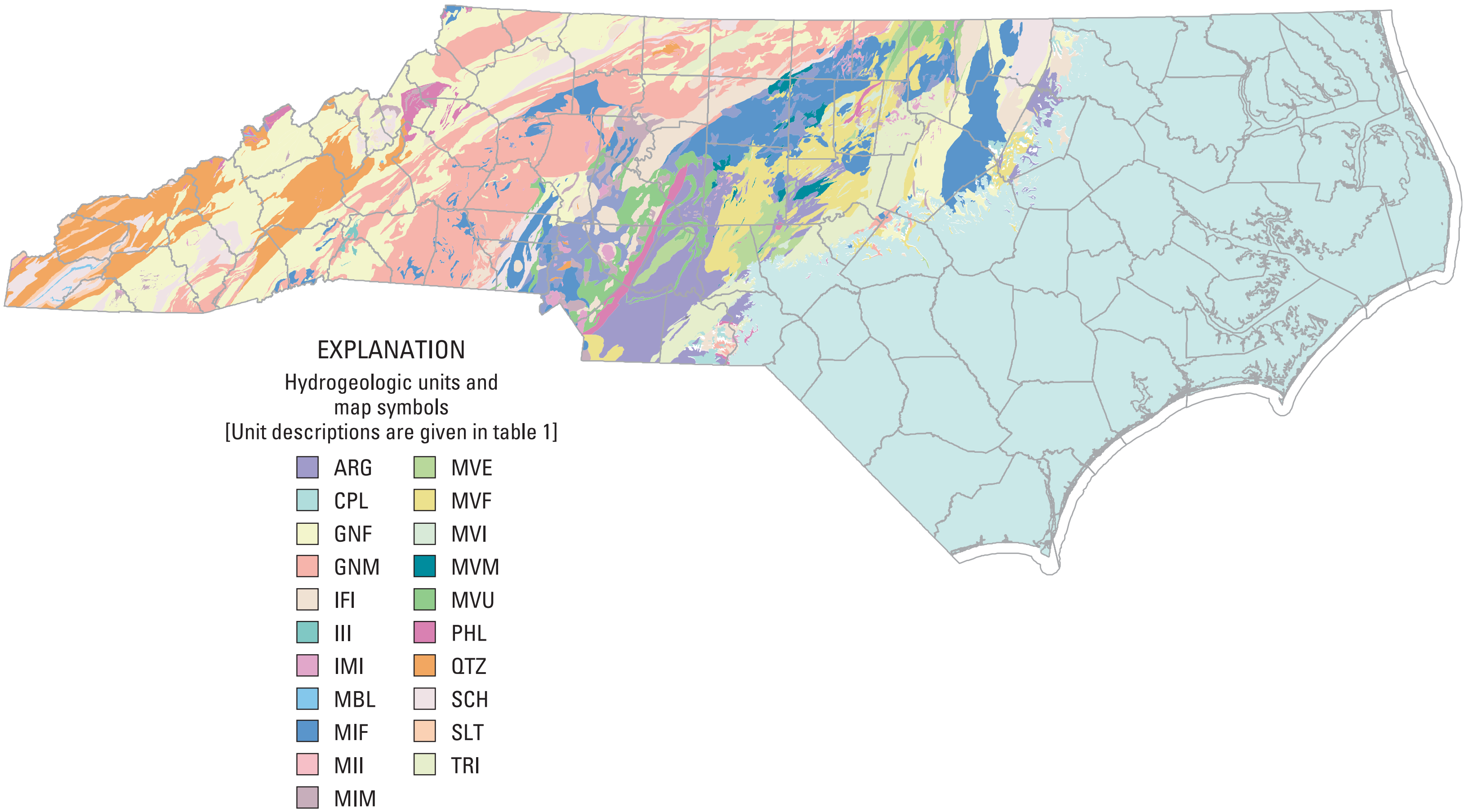
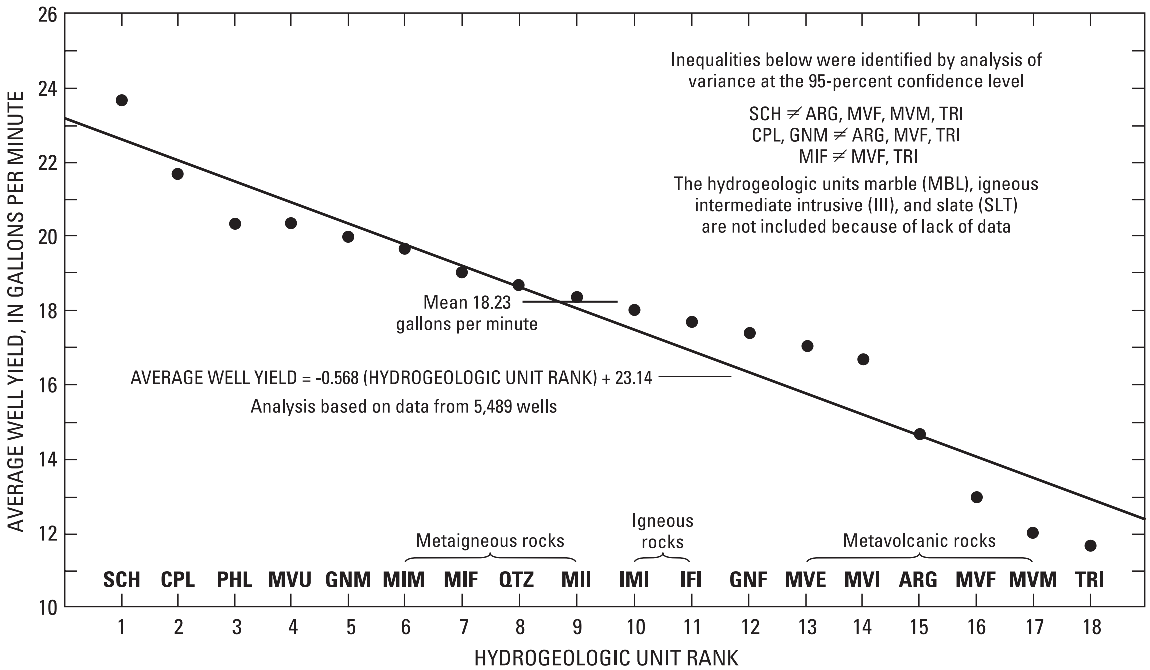


Figure 5. Hydrogeologic units within the Blue Ridge and Piedmont Provinces of North Carolina (from Daniel and Payne, 1990).



EXPLANATION

Hydrogeologic unit[a]			Hydrogeologic unit[a]		
Rank	Symbol		Rank	Symbol	
1	**SCH**	Schist	10	**IMI**	Igneous, mafic intrusive
2	**CPL**	Coastal Plain basement	11	**IFI**	Igneous, felsic intrusive
3	**PHL**	Phyllite	12	**GNF**	Gneiss, felsic
4	**MVU**	Metavolcanic, undifferentiated	13	**MVE**	Metavolcanic, epiclastic
5	**GNM**	Gneiss, mafic	14	**MVI**	Metavolcanic, intermediate
6	**MIM**	Metaigneous, mafic	15	**ARG**	Argillite
7	**MIF**	Metaigneous, felsic	16	**MVF**	Metavolcanic, felsic
8	**QTZ**	Quartzite	17	**MVM**	Metavolcanic, mafic
9	**MII**	Metaigneous, intermediate	18	**TRI**	Triassic sedimentary rocks

[a]Unit descriptions are given in table 1.

Figure 6. Average yield of wells of average construction in the hydrogeologic units of the Blue Ridge and Piedmont Provinces of North Carolina (modified from Daniel, 1989).

unit and the relation between well yield and the saturated thickness of regolith. The saturated thickness of regolith associated with a well is a computed characteristic described in Daniel (1989, p. A15).

Hydrogeologic Belts

The Blue Ridge and Piedmont Provinces are divided into a number of northeast-trending geologic belts (fig. 7) that provide a convenient and rational means of grouping the hydrogeologic units. Within a belt, rocks are to some degree similar with respect to general appearance, metamorphic rank, structural history, and relative abundance of igneous, metaigneous, metasedimentary, and metavolcanic rocks (Butler and Ragland, 1969). These northeast-trending belts tend to have distinct hydrogeologic properties (Daniel, 1989). Areally, the most significant are the Blue Ridge, Inner Piedmont, Charlotte, Carolina slate, and Raleigh belts. Two geologic belts important to this study have been added to the generally recognized belts. These are the Triassic basins and the Coastal Plain directly east of the Fall Line, where crystalline rocks are exposed along valleys and underlie sediments in interstream areas at shallow depth. A brief summary of the belts and the hydrogeologic units that constitute the belts is given in table 3.

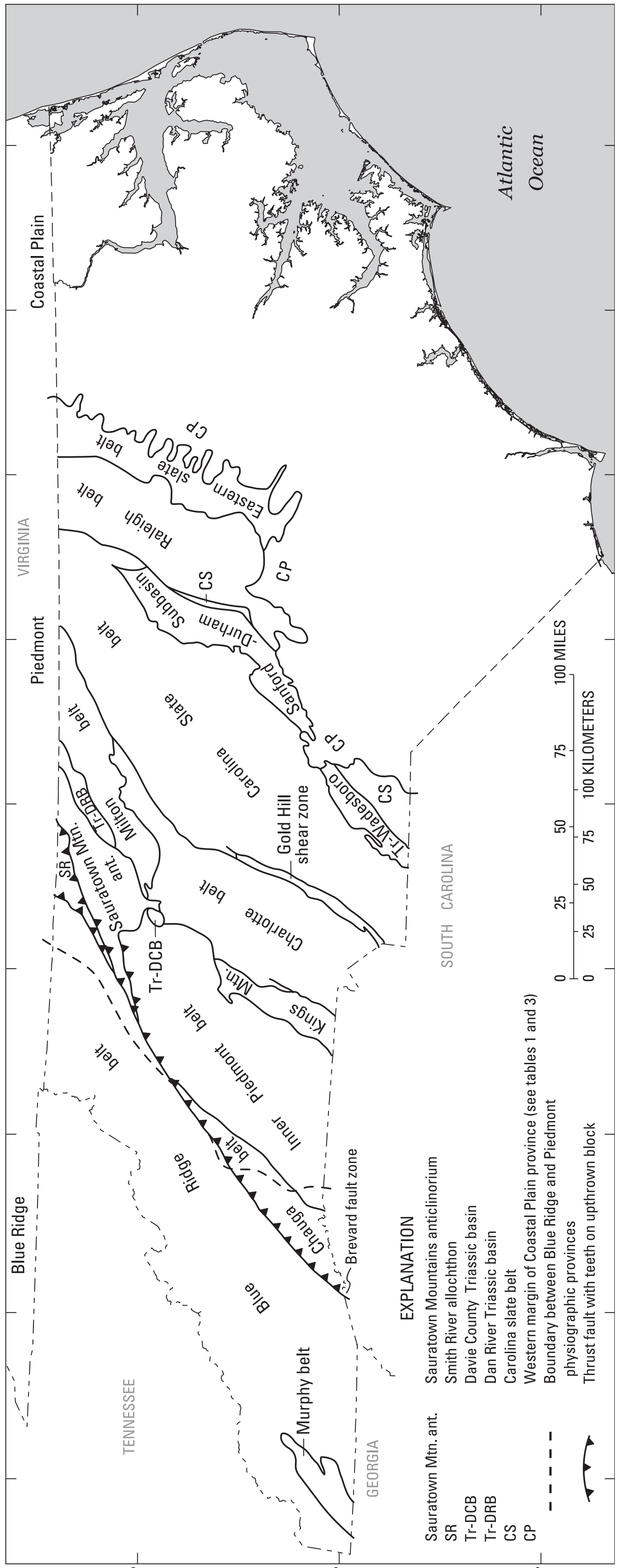


Figure 7. Geologic belts and some major structural features within the Blue Ridge and Piedmont Provinces of North Carolina (from Brown and Parker, 1985).

Table 3. Geologic belts of the Blue Ridge, Piedmont, and Coastal Plain Provinces of North Carolina

[From Daniel, 1989; hydrogeologic units are described in table 1]

Belt	Letter designation	Boundaries	Dominant hydrogeologic units
Murphy belt	MU	Surrounded by metasedimentary rocks of Blue Ridge belt.	SCH, SLT, MBL
Blue Ridge belt	BR	Sedimentary rocks of Valley and Ridge on northwest and Brevard fault zone on southeast.	GNF, GNM, SCH, QTZ, PHL
Chauga belt (includes Brevard fault zone)	CA	Blue Ridge belt on northwest, Inner Piedmont on southeast.	GNF, GNM
Inner Piedmont belt	IP	Chauga and Blue Ridge belts on northwest, Kings Mountain and Charlotte belts on southeast.	GNM, MIF
Smith River allochthon	SR	Blue Ridge belt on northeast and Sauratown Mountains anticlinorium on southeast.	GNF
Sauratown Mountains anticlinorium	SA	Smith River allochthon on northwest, Inner Piedmont belt on southwest, and Dan River Triassic basin and Milton belt on southeast.	GNM, GNF, QTZ
Kings Mountain belt	KM	Inner Piedmont belt on northwest and Charlotte belt on southeast.	SCH, MIF, GNF
Charlotte belt	CH	Kings Mountain and Inner Piedmont belts on northwest, Milton belt on north, Gold Hill shear zone and Carolina slate belt on southwest.	MII, MIF, MIM, IFI, MVU
Milton belt	MI	Igneous and metaigneous rocks of Charlotte belt on south, Carolina slate belt on southeast, Dan River Triassic basin and Sauratown Mountains anticlinorium on northwest.	GNM, GNF
Gold Hill shear zone	GH	Metavolcanic and metaigneous rocks of Charlotte belt on northwest and metavolcanic rocks of Carolina slate belt on southeast.	PHL
Carolina slate belt	CS	Gold Hill, Charlotte, and Milton belts on northwest, Coastal Plain on southeast.	ARG, MVE, MVU in southwestern half of belt—MVF, ARG, MVU, MIF, MII in northeastern half of belt
Raleigh belt	RA	Bordered by Carolina slate belt rocks on east and west, Coastal Plain sediments on the south.	MIF, GNF, SCH
Triassic basins	TR	Several bodies of sedimentary rock downfaulted into the metamorphic crystalline rocks of the Piedmont.	TRI
Coastal Plain	CP	Western margin of Coastal Plain Province.	CPL

HYDROLOGIC CONDITIONS IN THE STUDY AREA

Metamorphic and igneous crystalline rocks underlie most of the Blue Ridge and Piedmont Provinces. Because the underlying crystalline rocks are similar in character, these provinces are often grouped as one unit for hydrologic studies. The two provinces, however, have discernible differences in hydrology, largely because of differences in topographic relief, regolith thickness, and climate. Within the Piedmont crystalline rocks, extending from Nova Scotia to South Carolina (fig. 4), are large rift basins that have been filled with sedimentary deposits of Mesozoic age (Smoot and Robinson, 1988). The sedimentary rocks of the Mesozoic basins are distinct from the metamorphic and igneous crystalline rocks of the Blue Ridge and Piedmont and, therefore, comprise a separate hydrogeologic terrane.

The Blue Ridge-Piedmont ground-water system is composed of four elements (fig. 8). These components are (1) the unsaturated zone in the regolith, which generally contains the organic layers of the surface soil; (2) the saturated zone in the regolith; (3) the lower saturated regolith, which contains the transition zone between saprolite and bedrock; and (4) the fractured crystalline bedrock system.

The surficial or uppermost layer is composed of saprolite, alluvium, and soil, collectively referred to as regolith (Daniel and Sharpless, 1983). The thickness of

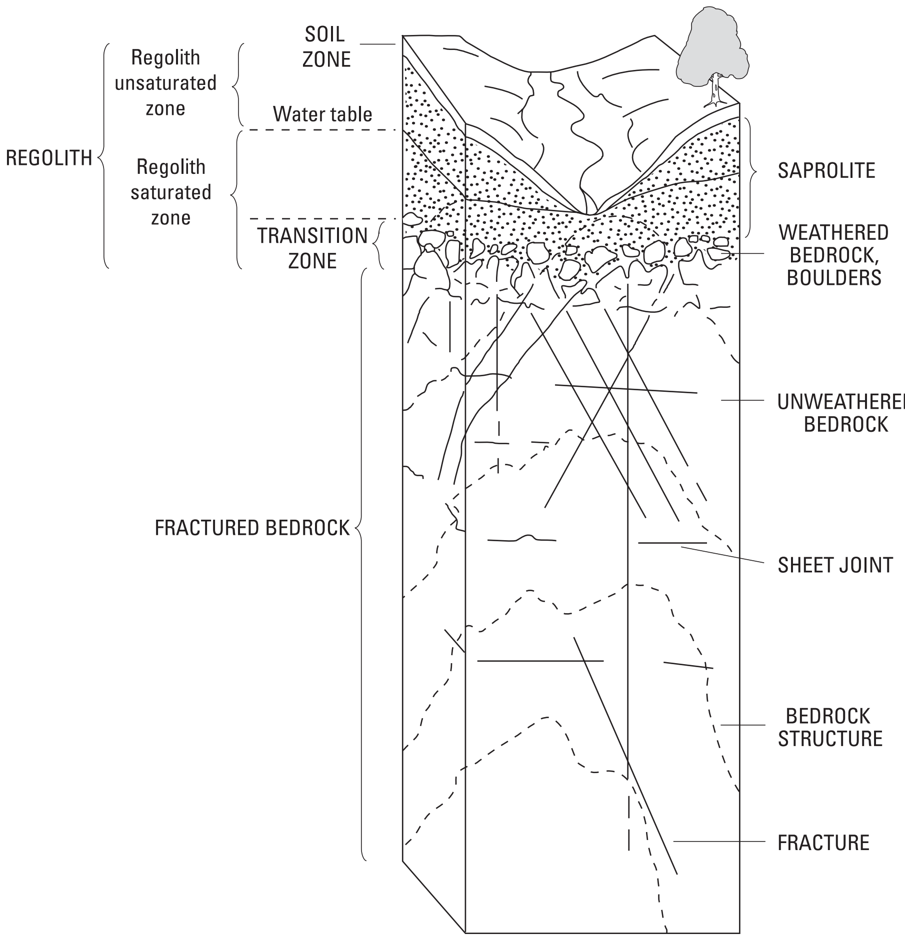


Figure 8. Principal components of the ground-water system in the Blue Ridge and Piedmont Provinces of North Carolina (from Harned and Daniel, 1992).

the regolith throughout the study area is highly variable and ranges from 0 to more than 150 ft. The regolith consists of an unconsolidated or semiconsolidated mixture of clay and fragmental material ranging in grain size from silt to boulders. With porosities that range from 35 to 55 percent, the regolith provides the bulk of the water storage within the Blue Ridge and Piedmont ground-water system (Heath, 1980).

Saprolite is the clay-rich, residual material derived from in-place weathering of bedrock. Saprolite commonly is highly leached and differs substantially in texture and mineral composition from the unweathered crystalline parent rock in which principal secondary openings are along fractures. Saprolite is granular material having principal secondary openings between mineral grains and rock fragments. Because saprolite is the product of in-place weathering of the parent bedrock, some of the textural features of the bedrock, including fractures, are retained. Saprolite usually is the dominant component of the regolith, in that alluvial deposits are restricted to locations of active and former stream channels and river beds; soil generally is restricted to a thin mantle on top of both the saprolite and alluvial deposits (fig. 8).

In the transition zone, unconsolidated material grades into bedrock. The transition zone consists of partially weathered bedrock and lesser amounts of saprolite. Particles range in size from silts and clays to large boulders of unweathered bedrock. The thickness and texture of the transition zone depend primarily on the texture and composition of the parent rock. The best defined transition zones usually are those associated with highly foliated metamorphic parent rock, whereas those of massive igneous rocks are poorly defined, with saprolite present between masses of unweathered rock (Harned and Daniel, 1992).

Stewart (1962) and Stewart and others (1964) tested saprolite cores collected in the vicinity of the

Georgia Nuclear Laboratory (in the Piedmont of northeastern Georgia) for several properties, including porosity, specific yield, and permeability. These data indicate that porosity, although variable, changes only slightly with depth through the saprolite profile; once the transition zone is reached, porosity begins to decrease sharply. The highest permeability values were found in the soil near land surface and within the transition zone.

Specific yield is the ratio of the volume of water a saturated rock (or other Earth material) will yield by gravity, to the total volume of rock. The distinction between porosity and specific yield is important; porosity indicates the total volume of pore space in the rock, whereas specific yield refers to the volume of water that will drain from the saturated rock. The two values are not equal because some water is retained within openings by surface tension and as a film on rock surfaces. The ratio of the volume of water retained to the total volume of rock is the specific retention.

Porosity and ground-water storage are the major differences in the water-bearing characteristics of the regolith and bedrock (fig. 9). The regolith can store water in pore spaces between rock particles. Crystalline bedrock, on the other hand, does not have any significant intergranular porosity; thus, water is stored in narrow planar openings formed along fractures. Joints, faults, and stress-relief fractures are among the most common secondary openings in crystalline bedrock. Joints and faults typically are the product of tectonic activity; stress relief fractures form as erosion removes overburden and the underlying rock expands. The porosity of regolith decreases with depth in the transition zone as the degree of weathering decreases (Stewart, 1962; Stewart and others, 1964). Porosity in fractured bedrock ranges from 1 to 10 percent (Freeze and Cherry, 1979, table 2.4), but porosities of 10 percent are atypical. Porosity values of 1 to 3 percent are more typical in the North Carolina Piedmont (Daniel and Sharpless, 1983).

As a general rule, the abundance of fractures and size of fracture openings in the crystalline bedrock decreases with depth. At depths below 750 ft, the pressure of the overlying material, or lithostatic pressure, holds fractures closed, and the porosity can be less than 1 percent (Daniel, 1989, 1992). Because of its higher porosity, the regolith functions as a reservoir that slowly feeds water downward into fractures in the bedrock (fig. 9). These fractures form an intricate interconnected network of pipelines that transmit water to springs, wetlands, streams, and wells.

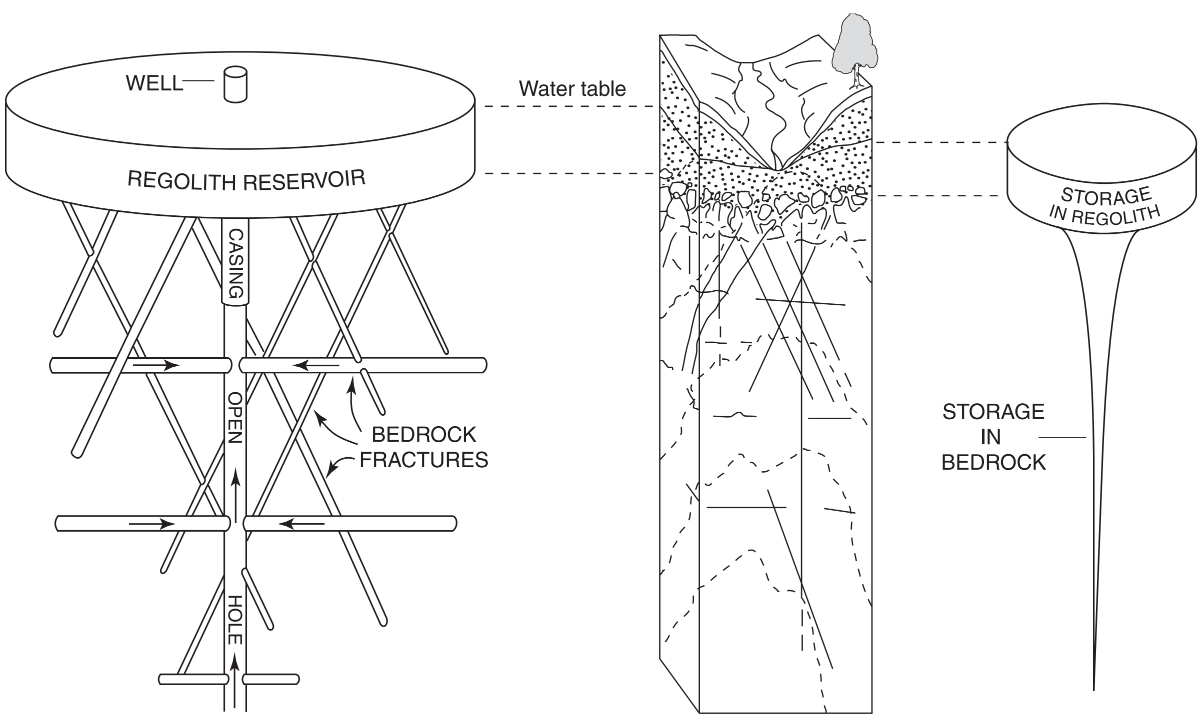


Figure 9. The reservoir-pipeline conceptual model of the Blue Ridge-Piedmont ground-water system and the relative volume of ground-water storage within the system (modified from Heath, 1984).

Small supplies of water that are adequate for domestic needs can be obtained from the regolith through large-diameter bored or dug wells. Most wells, however, especially where moderate supplies of water are needed, are relatively small in diameter and are cased through the regolith and finished with open holes, often of substantial depth, drilled into the bedrock. Being deeper, bedrock wells generally have much higher yields than regolith wells because they have a much larger available drawdown.

Because fractures in the bedrock decrease in size and abundance with depth, contamination of these aquifers is difficult to remediate, especially if the contaminant is heavier than water. The situation is even more acute if the contaminant has low solubility in water. Contaminants that settle or move into deeper parts of fractured-rock aquifers tend to become trapped as fracture widths become narrower and ground-water velocities diminish. The surface tension of dense, insoluble contaminants may be sufficient to hold the contaminants in place in narrow fractures (Pankow and Cherry, 1996; Wolfe and others, 1997).

Ground-Water Source and Occurrence

The continuous movement of water in the environment is referred to as the hydrologic cycle (Meinzer, 1942; Chow, 1964), and quantification of the various components of the hydrologic cycle is referred to as a water budget. The water budget of an area can be expressed by the following general form of a mass balance equation:

$$\text{Inflow} = \text{Outflow} \pm \text{Change in storage.} \qquad (1)$$

This simple expression can be expanded by including the various components of the hydrologic cycle that fall into the categories of inflow, outflow, and change in storage. The relation between these components is shown diagrammatically as follows:

Under natural conditions, at the watershed scale, precipitation represents 100 percent of the input to surface-water and ground-water supplies. Part of the precipitation is returned to the atmosphere by evaporation from soil, wet surfaces, and surface-water bodies and by transpiration by vegetation. These return paths to the atmosphere are collectively referred to as evapotranspiration.

Streamflow has two components: (1) surface runoff, which consists of overland flow from areas that cannot absorb precipitation as fast as it falls, and precipitation that falls directly onto bodies of water; and (2) ground-water discharge into the stream channel, also called base flow. Storage also has two components: (1) water stored in the ground and (2) water stored in surface-water bodies. The change in ground-water storage is the difference between ground-water recharge (from infiltration) and ground-water discharge (as base flow). The change in surface-water storage is the difference between inflow to and outflow from stream channels, lakes, and other surface-water bodies.

When these components of the water budget are analyzed on a monthly basis in the North Carolina Blue Ridge and Piedmont, a pattern, or seasonality, is apparent. The highest ground-water recharge occurs in the cooler, nongrowing season during the months of January through March, and the lowest ground-water recharge occurs at the height of the growing season during the months of June through September (Daniel and Sharpless, 1983, fig. 7). Seasonality in ground-water recharge is caused primarily by seasonal variations in the rate of evapotranspiration. Seasonal patterns in precipitation have less effect on recharge. In fact, long-term records indicate that precipitation in North Carolina is rather evenly distributed during the year, and the wettest months are commonly June and July, near the low point of seasonal ground-water recharge.

Components of the water budget that are important to this regional study include (1) the volume of water that is stored in the ground and (2) rates of recharge to and discharge from the ground-water system, which result in changes in ground-water storage. When rates of ground-water recharge exceed rates of discharge, the amount of

Inflow	=	Outflow			±	Change in storage		
Precipitation	=	Evapotranspiration	+	Streamflow	±	Ground water	±	Surface water
Rain + Snow		Evaporation + Transpiration		Overland runoff + Base flow		Ground-water recharge (from infiltration) – Ground-water discharge (as base flow)		Inflow to stream channels and lakes – Outflow from stream channels and lakes

ground water in storage increases and the water table rises. When rates of ground-water discharge (including withdrawals from wells) exceed rates of recharge, as usually occurs during droughts, the amount of ground water in storage decreases and the water table declines. When changes in ground-water storage are small, ground-water recharge is roughly equal to ground-water discharge. To account for seasonal variations in the water budget resulting from variations in precipitation, evaporation, and transpiration, it is useful to express components of the water budget on a yearly basis because annual variations tend to be small. Over longer periods, perhaps a decade or more, net changes in the water budget tend to be near zero. This assumes that ground water is not used to such an extent that long-term declines in the water table have occurred.

Ground-Water Recharge

Estimates of ground-water recharge rates in the Blue Ridge and Piedmont were made by analyzing long-term streamflow data from 11 selected gaging stations using an analytical technique for determining the ground-water component of total streamflow, which is known as hydrograph separation (Rorabaugh, 1964; Pettyjohn and Henning, 1979; Sloto, 1991; Rutledge, 1993; Rutledge and Daniel, 1994). The Blue Ridge-Piedmont drainage basins for which recharge characteristics were determined are shown in figure 10. Statistical summaries of average annual streamflow, overland runoff, ground-water discharge, and ground-water discharge as a percentage of average annual streamflow are presented in table 4. By assuming no long-term changes in ground-water storage, the ground-water component of streamflow (base flow) is considered to be equal to ground-water recharge.

Estimates of recharge on a regional scale are based on assumptions of uniform conditions in the underlying aquifers and in the drainage basins with respect to factors such as soils, topography, land use, and land cover, all of which affect infiltration. Because conditions in drainage basins rarely are uniform throughout the entire basin, the estimates may not precisely quantify recharge in all areas.

Assuming that ground-water discharge is equal to ground-water recharge, the average ground-water recharge in the 11 selected Blue Ridge-Piedmont drainage basins ranges from 3.3 in/yr (24 percent of average annual streamflow) in the Rocky River basin to 18.2 in/yr (73 percent of average annual streamflow) in the French Broad River basin (table 4). The average annual recharge for the 11 basins is 8.6 in/yr, or 47 percent of average annual streamflow.

Correlations between recharge rates and hydrogeologic units (and derived regolith) are not immediately apparent. None of the basins that were studied are sufficiently small enough to characterize recharge rates according to individual hydrogeologic units. All 11 basins contain multiple hydrogeologic units in varying proportions. Recharge rates also depend on other factors that vary from basin to basin. An important factor is the infiltration capacity of the soil, which depends not only on soil properties derived from weathering of the bedrock, but on land use and land cover. When land use and land cover are considered

Table 4. Water budgets of selected streams in the Blue Ridge and Piedmont Provinces of North Carolina

[Modified from Harned and Daniel, 1987; locations of gaging stations are shown in figure 10]

Map number (fig. 10)	Stream name	Average annual streamflow (inches)	Overland runoff (inches)	Ground-water discharge (inches)	Ground-water discharge as percentage of average annual streamflow (percent)
1	French Broad River	25.1	6.9	18.2	73
2	Second Broad River	19.2	6.8	12.4	65
3	Jacob Fork	26.4	13.9	12.5	47
4	Sugar Creek	23.8	16.2	7.6	32
5	Rocky River	13.2	9.9	3.3	24
6	Yadkin River	17.7	8.1	9.6	54
7	Reedy Fork	15.4	6.1	9.3	60
8	East Fork Deep River	15.1	8.9	6.2	41
9	Big Alamance Creek	13.4	7.1	6.3	47
10	Haw River	12.5	8.7	3.8	31
11	Neuse River	13.8	7.9	5.9	43
Average		17.8	9.1	8.6	47

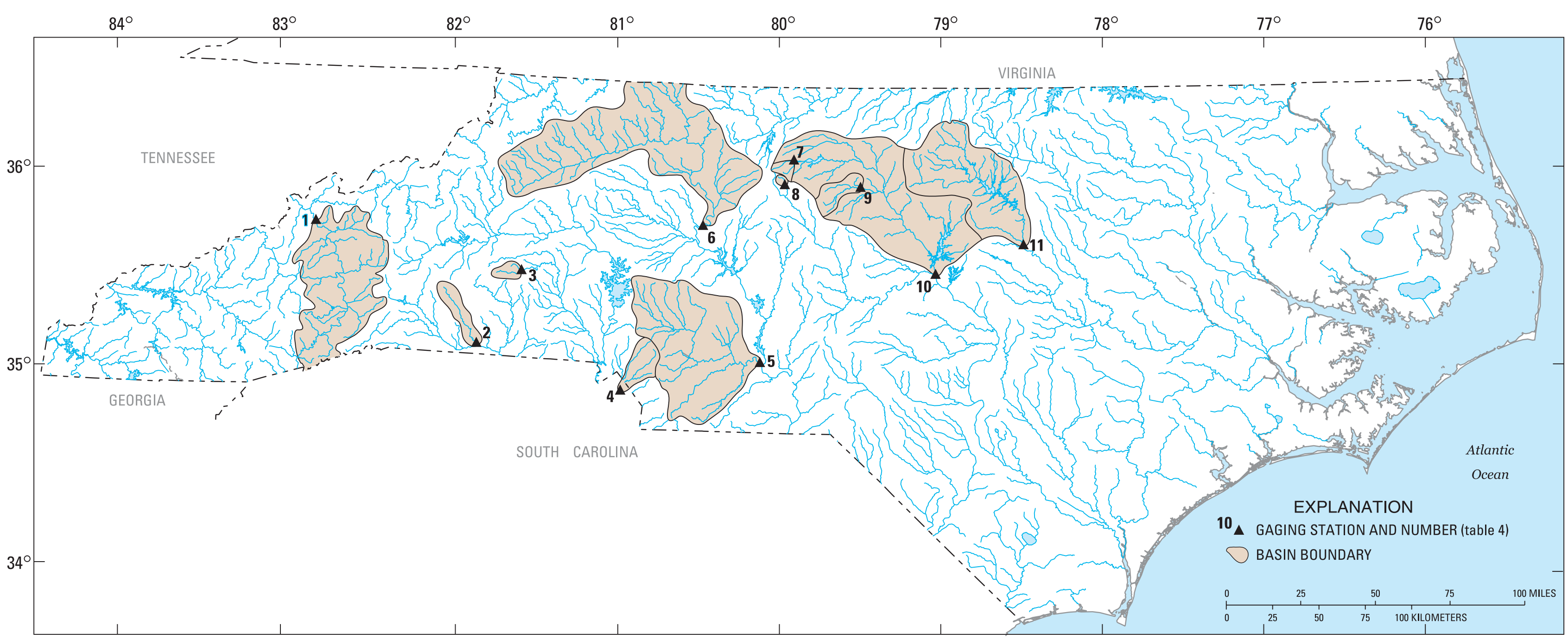


Figure 10. Locations of gaging stations and drainage basins in the Blue Ridge and Piedmont of North Carolina for which estimates of ground-water recharge were determined by the technique of hydrograph separation.

independently of other factors, recharge rates and infiltration capacities are highest in forested areas and lowest in urban areas. Recharge rates and infiltration capacities typically are intermediate in agricultural areas (Chow, 1964). Topography also is important because runoff rates are low on gentle slopes, allowing more time for infiltration. The cooler temperatures and shorter growing season observed at higher altitudes may explain the high ground-water recharge rate found in the French Broad River basin, which lies entirely within the Blue Ridge Province.

Recharge varies from month to month and year to year, depending on amounts and seasonal distribution of precipitation, evaporation, transpiration, land use, and other factors. Another important aspect of recharge and discharge involves timing. Recharge occurs during and immediately following periods of precipitation and, thus, is intermittent. Discharge, on the other hand, is a continuous process as long as ground-water levels are above levels at which discharge occurs. Between periods of recharge, however, ground-water levels decline, and discharge declines. Most recharge of the ground-water system occurs during late fall, winter, and early spring when plants are dormant and evaporation rates are low.

Estimates of ground-water recharge, whether determined by hydrograph separation or some other technique, are often needed to construct ground-water flow models and to calculate mass transport, time of travel, or other measures of advective ground-water movement. Some of the recharge estimates shown in table 4 are for large basins (fig. 10); these estimates may not be appropriate for site-specific studies because local hydrogeologic conditions and land use at a specific site may not be typical of an entire basin. For site-specific studies, local recharge estimates may have to be determined for small basins or subbasins similar to the estimates determined by Daniel (1996) for 12 basins and subbasins in Orange County and by Daniel and Harned (1998) for 15 basins and subbasins in Guilford County. If greater refinement of recharge estimates is needed for small areas within a basin or subbasin, apportionment of the watershed estimate based on local land use, slope, and soil type may be appropriate (Mew and others, 1996).

Ground-Water Storage

Nearly all ground-water storage in the Blue Ridge and Piedmont ground-water system is in the regolith. The quantity stored in the bedrock is small by comparison. Ground-water levels decline during the summer and early fall when atmospheric conditions enhance evaporation and plants transpire substantial quantities of water, and rise during the winter and early spring when plants are dormant.

The depth to the water table in the Blue Ridge and Piedmont Provinces varies from place to place and from time to time depending on the topography, climate, and properties of the water-bearing materials. Although climate and the water-bearing properties of different bedrock lithologies and regoliths can vary greatly on a regional basis, locally they can be quite similar. Therefore, topography probably has the greatest influence on the depth to the water table in a specific area (Daniel and others, 1997).

In stream valleys and areas adjacent to ponds and lakes, the water table may be at or very near land surface. On slopes, upland flats, and broad interstream divides of the Blue Ridge and Piedmont Provinces, the water table generally ranges from a few feet to a few tens of feet beneath the surface. On hills and rugged ridge lines, however, the water table can be at considerably greater depths. In effect, the water table typically is a subdued replica of the land surface. The depth to the water table and the relation of the water table to the saturated thickness of regolith reflect the timing of recharge, the amount of water in storage, and the movement of ground water to discharge areas.

Although higher rates of ground-water recharge typically occur during the months of January through March (Daniel and Sharpless, 1983), the water table usually does not reach its greatest height in the eastern and central Piedmont until May or June. The 2- to 3-month lag between the time of maximum ground-water recharge and the time of highest water table is attributed to the time required for recharge to move through the unsaturated zone to the water table. A similar lag was reported by Daniel and others (1997) for 36 wells tapping regolith and bedrock in the southwestern Piedmont of North Carolina, where peak recharge usually occurs during the months of February through April, but ground-water levels commonly are highest in July or August. The fact that peak recharge and ground-water levels lag about a month behind the eastern Piedmont is attributed to the higher elevation, cooler climate, and later start to the growing season in the southwestern Piedmont. In the Blue Ridge, the higher elevations result in even shorter growing seasons and lower temperatures than in the Piedmont. Seasonal changes in ground-water levels in the Blue Ridge reflect these climatic conditions with a longer period of seasonal high water table and shorter period of seasonal low water table when compared to the Piedmont.

The amount of ground water in storage can be estimated from the saturated thickness of regolith. Because regolith is unconsolidated and subject to collapse into open boreholes, well casing typically is installed through the regolith to the top of unweathered bedrock during the well-drilling process. Therefore, the depth of surface casing in a drilled well is a good approximation of regolith thickness in the Blue Ridge and Piedmont (Daniel and Sharpless, 1983; Snipes and others, 1983). The remainder of the borehole is completed as a self-supporting open hole drilled into the bedrock. By subtracting the depth to water from the depth of casing, an estimate of the saturated thickness of regolith is obtained. If the water level in the well is below the bottom of the casing, the saturated thickness of regolith is assumed to be zero.

Surface casing is usually set no more than 1 or 2 ft into fresh bedrock, just below the interface between the bedrock and the overlying regolith. Wells drilled in North Carolina since the passage of the North Carolina Well Construction Act of 1967 (Heath and Coffield, 1970), however, are required to have a minimum of 20 ft of casing regardless of the depth to bedrock. More recent revisions to the regulations require 35 ft of casing in wells tapping the argillites of the slate belt. Many of the records used by Daniel (1989) to estimate regolith thickness were for wells drilled prior to 1967. Records of casing depths as shallow as 1 ft in wells on bare-rock exposures were included in the data compilation. These data better reflect the natural range of depths to bedrock and, thus, provide for a more accurate approximation of regolith thickness.

A statistical summary of data on depth of well casing, depth to water, and estimated saturated thickness of regolith for wells in different topographic settings in the Piedmont is presented in Daniel (1989, table 5). The average depth of well casing for all wells in this data summary is 52.0 ft. The average depth to water is greatest beneath hills and ridges and least beneath valleys and draws. Consequently, the saturated thickness of regolith is least beneath hills and ridges (average 20.4 ft) and greatest beneath valleys and draws (average 33.6 ft). The saturated thickness of regolith beneath slopes (average 24.6 ft) is intermediate to these extremes. The average saturated thickness of regolith for all wells in the data summary is 24.0 ft.

The quantity of ground water available from storage at a specific site can be estimated from the following general relation:

$$\begin{aligned}&\text{available ground water in storage}\\&= \text{saturated thickness of regolith}\\&\times \text{specific yield.}\end{aligned} \tag{2}$$

In the absence of site-specific data, values of specific yield can be derived from the relation developed for northeastern Georgia (fig. 11A). Sufficient similarities exist between the Piedmont of northeastern Georgia and the Piedmont of North Carolina that this information can be used with reasonable limits of confidence. The depth of weathering, lithology of the underlying bedrock, and geologic structures are similar in both areas. Furthermore, Daniel and Sharpless (1983) report that dewatering of saprolite during a pumping test in a similar hydrogeologic setting (fractured mafic gneiss and schist) in Guilford County could be explained by a specific yield of 0.20.

Based on average thicknesses of saturated regolith presented by Daniel (1989, table 5) and the relations shown in figure 11B, the average quantity of available ground water in storage in the Piedmont is calculated to be 0.55 million gallons per acre (Mgal/acre) beneath hills and ridges, 0.77 Mgal/acre beneath slopes, and 1.22 Mgal/acre beneath valleys and draws. Overall, the average quantity of ground water available in the Piedmont is calculated to be 0.73 Mgal/acre.

Table 5. Properties of regolith at three well locations in the Piedmont northwest of Greensboro, North Carolina

[From Harned and Daniel, 1992; well locations and construction characteristics are given in Daniel and Sharpless, 1983; NA, not applicable]

Well pair numbers	Total regolith thickness (feet)	Soil and saprolite thickness (feet)	Transition zone thickness (feet)	Regolith saturated thickness on March 3, 1989 (feet)	Topography
Gu-383, AH-13	45.9	35.8	10.1	29.6	side of draw
Gu-385, AH-4	65.7	48.1	17.6	48.1	side of draw
Gu-386, AH-1	46.2	27.9	18.3	28.3	side of draw
Average	52.6	37.3	15.3	35.3	NA

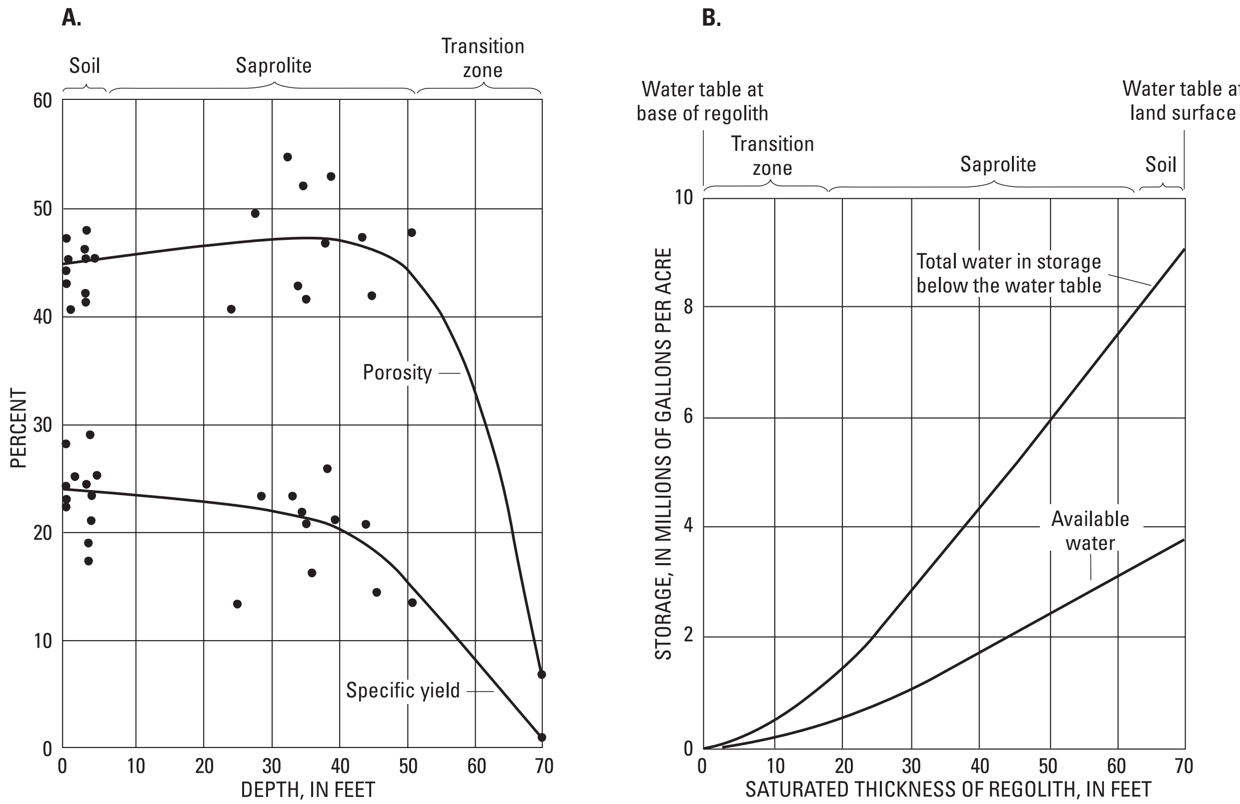


Figure 11. Relation of porosity and specific yield to total ground-water storage and available water in the regolith (from Daniel and others, 1997, fig. 27). A. Variation of porosity and specific yield with depth in the regolith (modified from Stewart, 1962); B. Total ground water in storage below the water table and water available by gravity drainage.

Ground-water storage in the Blue Ridge is similar to ground-water storage in the Piedmont. The least amount of available water is stored beneath hills and ridges, and the greatest amount is stored beneath valleys and draws. The average quantity of available ground water in the Blue Ridge of North Carolina is calculated to be 0.97 Mgal/acre.

Where a discrete transition zone is present between the saprolite and the underlying unweathered bedrock (Harned and Daniel, 1992), the relations between porosity and depth and specific yield and depth are nonlinear. Consequently, equation 2 becomes nonlinear, and a plot of this relation is nonlinear, as shown in figure 11B. The quantity of water available from storage in the regolith can be estimated from figure 11B. Although ground-water levels fluctuate seasonally, in the absence of being over pumped, few wells in the Blue Ridge or Piedmont go dry, suggesting that seasonal fluctuations of the water table occur primarily within the saprolite. As shown in figure 11B, water available from storage in the saprolite follows a more or less linear part of the relation with a specific yield of about 0.20 (fig. 11A). Therefore, the contribution to base flow from water in storage in the saprolite can be estimated by the linear equation:

$$\text{water from storage} = 0.20 \times \text{change in water table.} \quad (3)$$

Based on this equation and a 4- to 12-ft natural annual variation in the water table (Daniel, 1996; Daniel and others, 1997; Daniel and Harned, 1998), the quantity of water in storage is estimated to increase or decrease by 0.31–0.89 Mgal/acre in 1 year.

Ground-Water Flow System

The ground-water flow system serves two hydraulic functions: (1) it transmits water from recharge areas to discharge areas and (2) it stores water to the extent of its porosity. Thus, the ground-water system serves as both a conduit and a reservoir. In most hydrogeologic settings, ground-water systems are more effective as reservoirs than as conduits.

Water from precipitation enters the ground-water system in recharge areas, which generally include all the land surfaces higher than the adjacent stream valleys. A conceptual view of the ground-water flow system for a typical area in the North Carolina Blue Ridge or Piedmont is shown in figure 12. After infiltration, water slowly moves downward through the unsaturated zone. Water moves vertically and laterally through the saturated zone, discharging as seepage springs on steep slopes and as bank and channel seepage into streams, lakes, or swamps where the saturated zone is near land surface. Some ground water is returned to the atmosphere by evapotranspiration (soil moisture evaporation and plant transpiration). In the regolith, ground-water movement primarily is through intergranular flow, although relict rock fabric and structure can influence ground-water movement. In bedrock, ground-water flow is through fractures, and the flow paths from recharge areas to discharge areas commonly are more circuitous than those in the regolith.

Transition Zone Between Saprolite and Bedrock

In the transition zone, unconsolidated saprolite grades into bedrock. The transition zone consists of partially weathered bedrock and lesser amounts of saprolite, with particles ranging in size from clays to large boulders of unweathered bedrock (fig. 8). The thickness and texture of this zone depend largely on the texture and composition of the parent rock. Well-defined transition zones usually are associated with highly foliated metamorphic parent rock, whereas transition zones associated with massive igneous rocks commonly are poorly defined, having saprolite present between masses of unweathered rock. A diagram showing how the transition zone can vary because of different rock type is presented in figure 13. The incipient planes of weakness produced by mineral alignment in the foliated rocks facilitates separation at the onset of weathering, resulting

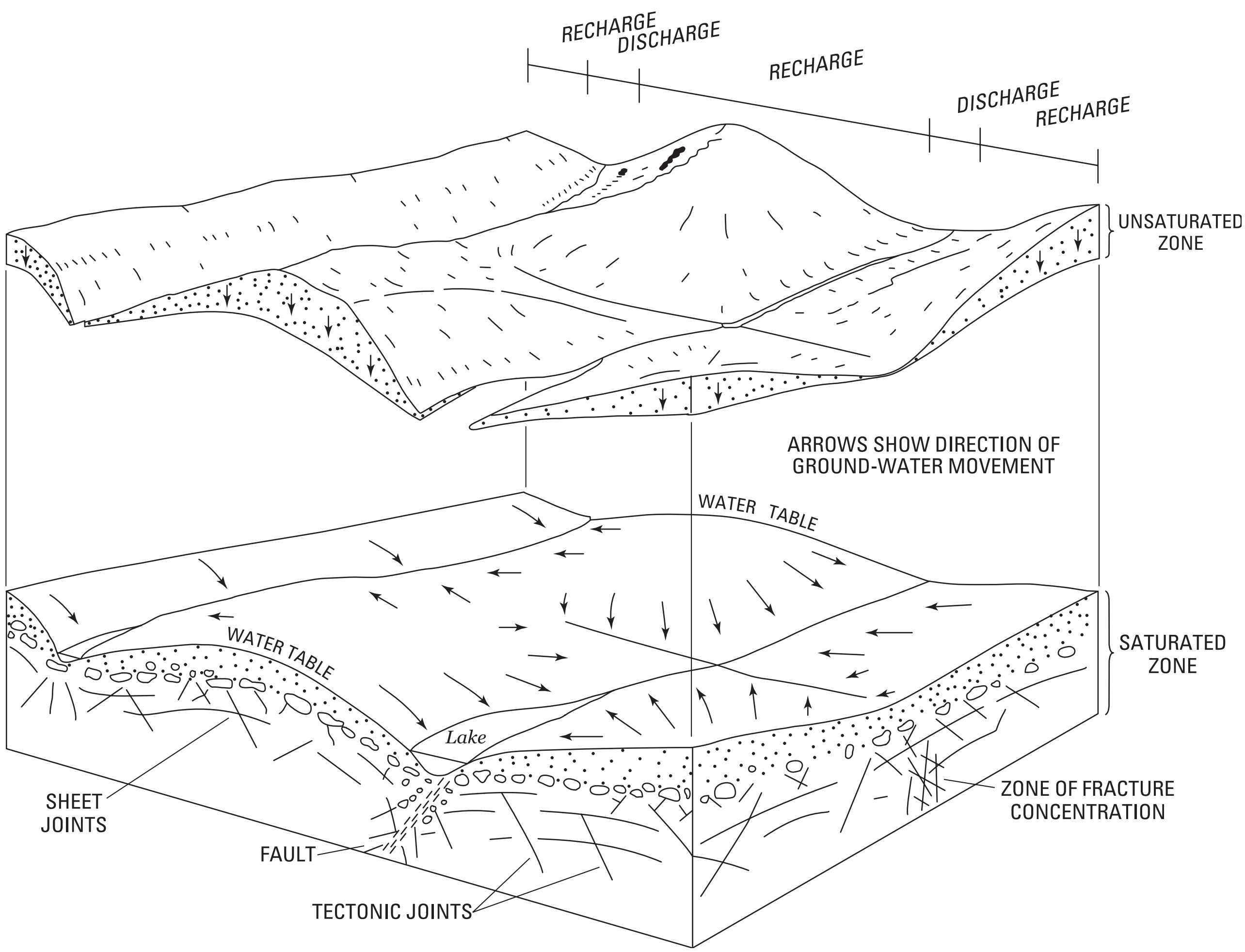


Figure 12. Conceptual view of the North Carolina Blue Ridge and Piedmont ground-water flow system showing the unsaturated zone (lifted up), the water-table surface, the saturated zone, and directions of ground-water flow (from Daniel, 1990b).

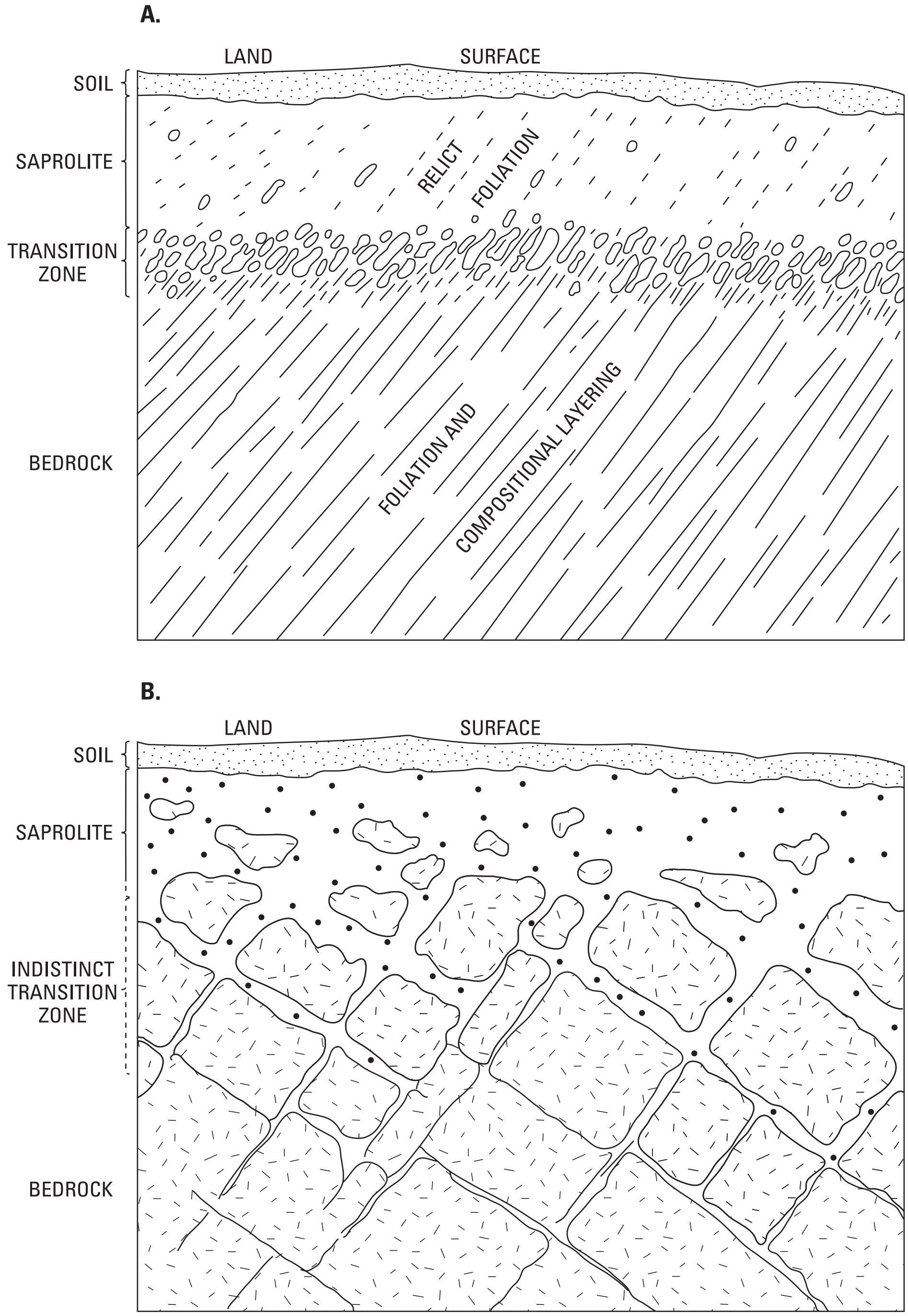


Figure 13. Conceptual variations of transition zone thickness and texture that develop on different parent rock types (from Harned and Daniel, 1992). A. A distinct transition zone on highly foliated schists, gneisses, and slates; B. An indistinct transition zone on massive bedrock.

in numerous rock fragments. More massive rocks do not possess these closely spaced planes of weakness, so weathering tends to progress along more widely spaced fractures, resulting in a less distinct transition zone.

In the North Carolina Piedmont, 90 percent of the records for cased bedrock wells indicate that the combined thicknesses of the regolith and transition zones is 97 ft or less (Daniel, 1989). Data for three pairs of wells drilled at a test site in Guilford County, North Carolina (table 5), indicate that the average transition zone in that area is about 15 ft thick. Transition zones identified in Georgia (Stewart, 1962) and Maryland (Nutter and Otton, 1969) were described as being more permeable than the upper regolith, and even slightly more permeable than the soil zone (fig. 14). This observation is substantiated by reports from well drillers of so-called "first water," "sand," and "boulders" at the base of the regolith (Nutter and Otton, 1969).

The high permeability of the transition zone probably is the result of incomplete weathering in the lower regolith. Chemical alteration of the bedrock has progressed to a stage of mineral expansion and extensive fracture development in the crystalline rock, yet it has not progressed so far that formation of clays and other weathering by-products has been sufficient to clog the fractures. An idealized weathering profile shown in figure 14 (Nutter and Otton, 1969) illustrates that as the degree of weathering increases, clay fractions also increase, which results in decreased permeability in the saprolite as compared to the transition zone.

The presence of a zone of high permeability on top of the bedrock may create a zone of increased ground-water flow in the ground-water system. For example, well drillers may find water at a relatively shallow depth, yet complete a dry hole after setting casing through the regolith and transition zone and into the unweathered bedrock. In this case, although ground water probably is present and moving within the transition zone, the dry hole indicates a poor hydraulic connection between the regolith reservoir, the bedrock fracture system, and the well.

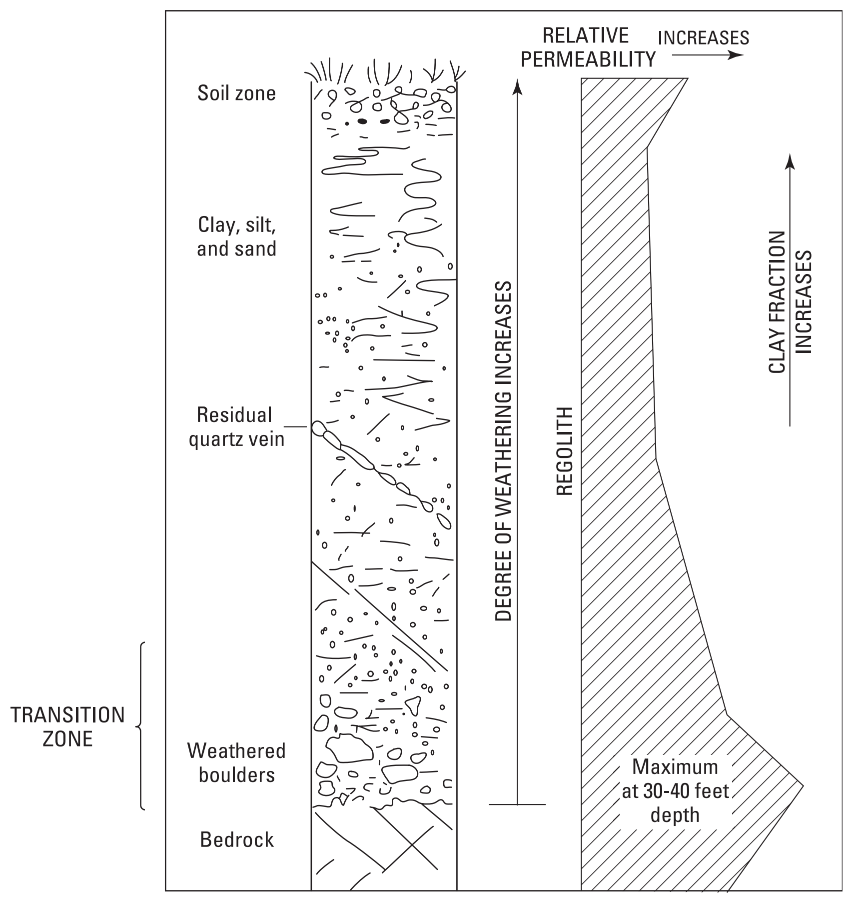


Figure 14. An idealized weathering profile through the regolith, and relative permeability (modified from Nutter and Otton, 1969).

The transition zone also may serve as a conduit for rapid movement of contaminants to nearby wells, or to streams with channels that are cut into or through the transition zone. How rapidly a contaminant moves through the system may largely be a function of the characteristics of the transition zone. If the ground water is contaminated, a well-developed transition zone will serve as a conduit of rapid movement for the contaminated water. The transition zone in figure 15 serves as a conduit for landfill leachate that eventually discharges to a local stream, which has incised into the transition zone. Because the distance from the point where water enters the terrestrial part of the hydrologic cycle in the Piedmont to where water discharges to a stream commonly is less than half a mile, contaminants entering the ground-water system and moving through the transition zone can rapidly become dispersed to surface-water bodies.

Figure 15 also illustrates how the thickness of the transition zone (table 5) can be determined. The depth of the bored well, completed to auger refusal, indicates the thickness of soil and saprolite. The depth to unweathered rock, as approximated by the casing depth in the drilled well, gives the total regolith thickness. By subtracting casing depth in the bored well from casing depth in the drilled well, an estimate of the thickness of the transition zone is obtained.

HYDROGEOLOGIC TERRANES

Understanding the hydrogeology of the Blue Ridge and Piedmont study area is complicated by the fact that the geology is complex and the porosity and permeability in the bedrock is almost exclusively secondary. As a result, the permeability is extremely variable, and not easily defined for a particular geologic formation or even a particular rock type. Consequently, the distinction between aquifers and confining units, which is the usual approach for describing the hydrogeologic framework of an area, is obscured. A more useful approach is to divide the study area into hydrogeologic terranes based upon factors related to the occurrence and distribution of secondary porosity and permeability.

For the purpose of this discussion, a hydrogeologic terrane is defined primarily by a combination of rock type, regolith conditions, and topographic setting, all of which are relatively homogeneous with respect to (1) the water-yielding potential of the earth materials, as indicated by the specific capacity of wells or base flow of streams; (2) ground-water storage; and (3) ground-water quality.

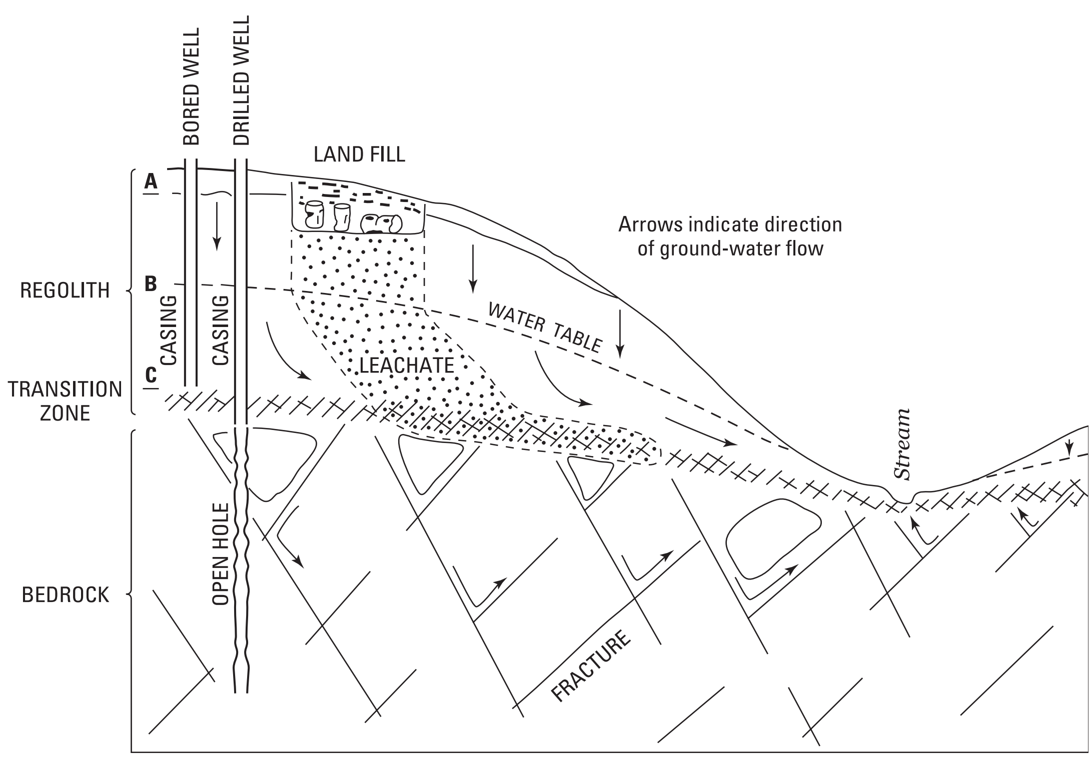


Figure 15. The transition zone between bedrock and saprolite functioning as a primary transmitter of contaminated ground water to a stream (from Harned and Daniel, 1992).

Currently, it appears that terranes are most easily distinguished primarily on the basis of rock type and secondarily by consideration of rock texture, regolith thickness and texture, rock structure, topographic setting, and nongeologic factors, some of which are not well understood. In general, water-yielding characteristics of the various hydrogeologic terranes within the Blue Ridge and Piedmont Provinces (table 6) are highly dependent on the saturated thickness of the regolith and transition zone. Therefore, variability in the thickness and texture of the regolith, which can store a substantial amount of ground water, is perhaps the most important of the secondary factors.

The USGS identified four hydrogeologic terranes in the Blue Ridge and Piedmont Provinces as part of the Appalachian Valleys-Piedmont Regional Aquifer-System Analysis (APRASA) study (Swain and others, 1991). The four terranes include (1) massive or foliated crystalline rocks mantled by thick regolith, (2) massive or foliated crystalline rocks mantled by thin regolith, (3) metamorphosed carbonate rocks, and (4) sedimentary rocks of the Mesozoic basins (table 6). These hydrogeologic terranes are thought to be associated with local or intermediate flow systems as described by Toth (1963).

The ground-water hydrology of the study area is best described in terms of conceptual flow systems. For the purpose of this study, a conceptual flow system is, in most cases, the three-dimensional flow net that is perceived to exist within a hydrogeologic terrane. In accordance with work by Toth (1963), local and intermediate systems of ground-water flow have been identified in the study area. Local flow systems mainly occur at depths shallower than 800 ft in the Blue Ridge and Piedmont Provinces; they commonly occur between adjacent drainage basin divides that range from a few thousand feet to a few miles apart. Analyses to date suggest that local flow systems represent greater than 95 percent of total ground-water flow (Daniel, 1989; Daniel and others, 1997). Conversely, the intermediate flow systems likely range in depth from 800 to 5,000 ft and traverse adjacent drainage basin divides in places. The intermediate flow systems probably represent less than 5 percent of the total ground-water flow. The hydrogeologic terranes discussed in this report are more closely associated with local flow systems than with intermediate flow systems. Deep, confined flow systems (Hobba and others, 1979, figs. 12, 13) are thought to be absent in these terranes, but if present, the quantity of ground water in circulation likely would be insignificant relative to the shallower, more localized, systems.

Because the sedimentary rocks of the Mesozoic basins are distinct from the metamorphic and igneous crystalline rocks of the Piedmont and Blue Ridge, the hydrogeology of the Blue Ridge and Piedmont Provinces has been divided into two distinct geologic settings based on differences in lithology—(1) crystalline-rock terranes, which make up 86 percent of the total Piedmont area and all of the Blue Ridge area, and (2) sedimentary-rock terranes of the early Mesozoic basins, which make up 14 percent of the Piedmont.

Although metamorphosed carbonate rocks, as discussed in a previous section, can contain substantial quantities of ground water, metamorphosed carbonate rocks in North Carolina are limited almost exclusively to the Murphy and Blue Ridge belts in the Blue Ridge Province. No large bodies of metamorphosed carbonate rock are present in the North Carolina Piedmont. Because of their limited areal extent and relatively low well yields in North Carolina, the metamorphosed carbonate rocks are grouped with other crystalline rocks for the purpose of describing hydrogeologic terranes in this report. The hydrogeologic terranes important to this study are described in the following sections.

Core samples from the North Carolina State University Upper Piedmont Agricultural Research Station, Rockingham County, North Carolina *(photo taken by D.J. Geddes, Groundwater Section, Division of Water Quality, North Carolina Department of Environment and Natural Resources).*

Table 6. General hydrologic characteristics of the hydrogeologic terranes of the Blue Ridge and Piedmont Provinces within the Appalachian Valleys-Piedmont Regional Aquifer-System Analysis (APRASA) study area

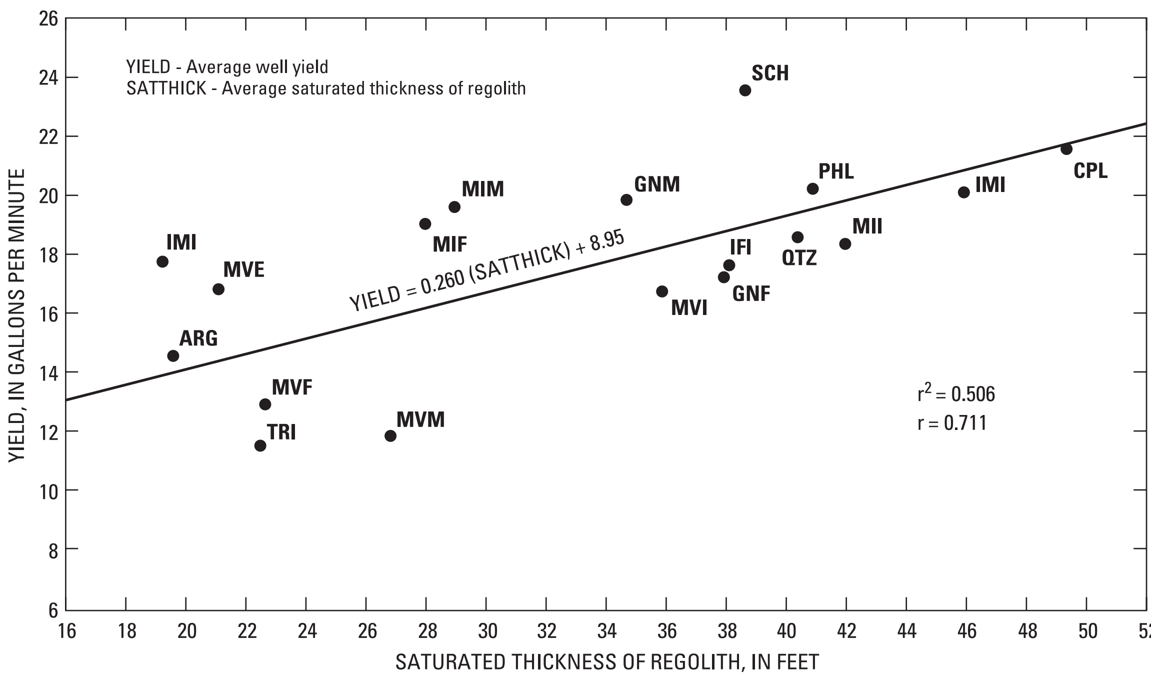
[Modified from Swain and others, 1991; ≤, less than or equal to]

Hyrogeologic terrane	Hydrologic characteristics								
	Topographic relief	Recharge	Discharge	Type of porosity or permeability	Type of flow	Depth of flow, in feet	Confined or unconfined	Regolith storage	Well yield
Massive or foliated crystalline rocks, thick regolith	Low to high	Precipitation on topographic highs	To streams	Intergranular in regolith, fracture	Diffuse, fracture	Shallow to intermediate, ≤ 800	Mostly unconfined	Large	Proportional to regolith thickness.
Massive or foliated crystalline rocks, thin regolith	Low to high	Precipitation on topographic highs	To streams	Fracture	Fracture	Shallow (mostly) to intermediate, ≤ 500	Unconfined	Small	Low.
Metamorphosed carbonate rocks	Low to moderate	Precipitation on topographic highs	To streams	Dissolution openings, some fractures	Conduit, fracture	Shallow	Unconfined	Small to moderate	Variable, some very high.
Mesozoic sedimentary basins	Low to moderate	Precipitation on topographic highs	To streams	Intergranular, some fractures	Diffuse, fracture	Shallow (mostly) to intermediate, ≤ 800	Mostly unconfined	Small	Variable, decreasing from north to south.

Massive or Foliated Crystalline Rocks Mantled by Thick Regolith

Although most wells in the Blue Ridge and Piedmont Provinces are open to fractured crystalline rocks, storage characteristics of the overlying regolith probably control the long-term quantity of water (sustained yield) available to wells (fig. 16). The thickness of regolith overlying crystalline rocks is highly variable and ranges from 0 to more than 150 ft. As defined for this study, "thick regolith" is regolith that is greater than 50 ft thick. The water-yielding capacity of the rocks in this hydrogeologic terrane is dependent upon not only the saturated thickness of regolith but also the density, width, spacing, and interconnectivity of the fractures in the crystalline rocks.

The hydrogeologic units producing the lowest well yields also tend to be the units with the least saturated thicknesses of regolith (compare figs. 6 and 16); most of these units belong to the category of metavolcanic rocks and the Triassic sedimentary rocks (TRI) in the miscellaneous category (table 1). The units producing intermediate well yields and having intermediate values of saturated thickness of regolith belong, in general, to the igneous and metaigneous rock categories. The units with the highest well yields and greatest saturated thicknesses of regolith belong to the category of metasedimentary rocks and the Coastal Plain basement rocks (CPL) in the



EXPLANATION

Hydrogeologic unit[a]		Hydrogeologic unit[a]	
Symbol		Symbol	
IMI	Igneous, mafic intrusive	**MVI**	Metavolcanic, intermediate
ARG	Argillite	**GNF**	Gneiss, felsic
MVE	Metavolcanic, epiclastic	**IFI**	Igneous, felsic intrusive
TRI	Triassic sedimentary rocks	**SCH**	Schist
MVF	Metavolcanic, felsic	**QTZ**	Quartzite
MVM	Metavolcanic, mafic	**PHL**	Phyllite
MIF	Metaigneous, felsic	**MII**	Metaigneous, intermediate
MIM	Metaigneous, mafic	**MVU**	Metavolcanic, undifferentiated
GNM	Gneiss, mafic	**CPL**	Coastal Plain basement

[a]Unit descriptions are given in table 1.

Figure 16. Relation of average well yield to the average saturated thickness of regolith for hydrogeologic units in the Blue Ridge and Piedmont Provinces of North Carolina.

miscellaneous category (table 1). For wells that tap the Coastal Plain basement rocks east of the Fall Line, Coastal Plain sediments function as a layer of regolith and store water that recharges fractures in the underlying bedrock. Wells in the CPL unit have some of the highest yields and greatest saturated thicknesses of regolith. Although there are exceptions and some overlap in categories of hydrogeologic units, a general pattern is apparent in figure 16 that indicates the saturated thickness of regolith (and by implication, the total thickness of regolith) and well yield correlate with hydrogeologic units that are classified according to their water-bearing potential and susceptibility to weathering, as discussed in the “Hydrogeologic Units” section.

Foliated crystalline rocks generally are anisotropic in terms of physical properties, such as orientation of fractures and primary permeability. Fractures typically are at high angles to bedding and foliation. In the eastern and southeastern United States, compressive forces that formed the Appalachian Mountains were oriented generally northwest to southeast. Bedding and compositional layering (including schistosity and gneissic banding) tend to be oriented northeast to southwest, and fractures tend to be oriented northwest to southeast, although local variation does occur. Schistose rocks contain minerals, such as mica and chlorite, that have laminated-type cleavage planes and are able to withstand extreme folding and deformation without creating any major secondary permeability. As a result, wells completed in foliated, schistose rocks generally yield only small amounts of water.

This hydrogeologic terrane has the highest average water-yielding capability for the Blue Ridge and Piedmont. Based on data from 1,421 bedrock wells located throughout the 65-county study area, the average thickness of regolith in this terrane is 82.0 ft and the average yield is 20.2 gal/min.

This terrane is most commonly identified with areas that have broad interstream divides and gentle relief. In these areas, stream channels typically are not deeply incised and have not eroded through the underlying regolith into bedrock. The rate of weathering at the regolith-bedrock boundary apparently exceeds, or at least keeps pace with, the rate of erosion at the land surface. The thickest regolith tends to occur beneath the interstream uplands and in areas overlying fracture zones that have facilitated deep weathering.

Massive or Foliated Crystalline Rocks Mantled by Thin Regolith

Massive crystalline rocks that are fractured can be locally important sources of ground water; however, storage generally is small within the fractures. In areas of North Carolina, porosities of 1 to 3 percent are common for the fractured rocks (Daniel and Sharpless, 1983). Yields of wells open to massive, unmantled, fractured rocks must be sustained by an extensive fracture network connected to a surface-water body or nearby area with saturated regolith; otherwise, well yields will be small.

As defined for this study, "thin regolith" is regolith that is 50 ft or less in thickness. Based on data from 1,723 bedrock wells located throughout the 65-county study area, the average thickness of regolith in this terrane is 30.1 ft—values fall within a range of 1–50 ft, and the average yield is 15.2 gal/min.

This terrane is identified most commonly with areas that have sharp-crested ridges, mountains, and steep hillsides. In these areas of rugged relief, stream channels typically are deeply incised and have eroded through the underlying regolith into bedrock. Beneath the ridges, mountains, and steep hillsides, the rate of weathering at the regolith-bedrock boundary apparently cannot keep pace with the rate of erosion at the land surface. As a result, regolith tends to be thin or absent, and bedrock outcrops can be found at land surface.

Sedimentary Rocks in the Early Mesozoic Basins

Ground water in sedimentary rocks within the early Mesozoic basins of the eastern United States (fig. 4) is stored and transmitted primarily through a complex network of joints, fractures, faults, and bedding planes. To a lesser extent, water moves through interstitial pore spaces and locally enlarged solution channels. Unfractured Mesozoic sedimentary rock typically has a negligible capacity to store and transmit water. Fine-grained rocks—siltstones, claystones, shales—often predominate, and the primary porosity that originally existed in the rocks has commonly been reduced by compaction and cementation. Additionally, permeability generally decreases with increasing depth below land surface. Well yields tend to decrease substantially from north to south along this band of sedimentary basins; in fact, yields of wells tapping the rocks of the Durham, Sanford, and Wadesboro subbasins in North Carolina and South Carolina (fig. 4) are among the lowest in the Piedmont.

Some preferential alignment is typical of secondary openings in consolidated-rock aquifers of the early Mesozoic basins; thus, the aquifers are anisotropic to some degree. In wells open to the Brunswick Group in the Newark basin (basin 15, fig. 4), drawdown was noted in an observation well 2,400 ft from a pumped well in a direction parallel to the strike of the formation beds, whereas no drawdown was evident in observation wells 600 ft from a pumped well in a direction perpendicular to the strike (Herpers and Barksdale, 1951). Similar observations of the anisotropy of the Brunswick Group have been documented by Vecchioli and others (1962) and Vecchioli (1965).

Preferential flow along strike probably is caused by variable degrees of fracturing in dipping beds. In a highly fractured bed, horizontal flow in the direction of strike may not be impeded by structural boundaries, but horizontal flow in the direction of dip may be bounded by adjacent, relatively unfractured beds and by the closure of fractures at depth.

The Mesozoic basins (fig. 4) contain beds or rock units that are significant aquifers locally, particularly in the northern Piedmont (Pennsylvania and New Jersey). The most productive water-yielding zones in the sedimentary rocks are in fractured red shale, sandstone, and conglomerate. Fractured-shale and sandstone aquifers yield as much as 1,500 gal/min in the basins in northern Virginia, Pennsylvania, and New Jersey (Carswell and Rooney, 1976; Nemickas, 1976). Black mudstones, basaltic rocks, diabase dikes and sills, and thermally metamorphosed rocks in the sedimentary basins commonly produce lower yields. These hydrogeologic units are tapped primarily for domestic supplies, and well yields generally are less than 5 gal/min, although there are notable exceptions for wells tapping some of the thicker, more highly fractured diabase dikes. In North Carolina, it is not uncommon when locating well sites in the Durham, Sanford, and Wadesboro subbasins (fig. 4) to conduct field mapping or magnetometer surveys in an effort to locate diabase dikes. In these southern basins, wells drilled into dikes commonly have higher yields than wells drilled into the surrounding fine-grained sedimentary rocks.

More than 10 percent of the ground water pumped within the northern Piedmont during 1985 was from the Newark basin (basin 15, fig. 4; Swain and others, 1991). The highest yielding wells are large-diameter (10 in. or more), relatively deep (200 to 600 ft deep) wells used for public supply and industry. Yields of 500 gal/min are common from these wells. Lowest yielding wells are small-diameter (6 in. or less) domestic wells, which generally are less than 250 ft deep. Yields of 10 to 20 gal/min are common from these wells.

In contrast to the Mesozoic basins in the northern Piedmont, the Mesozoic basins in North Carolina produce only small supplies of water. With an average well yield of 11.6 gal/min (Daniel, 1989), the TRI hydrogeologic unit (table 1; fig. 6) has the lowest average yield of any hydrogeologic unit in the Blue Ridge or Piedmont of North Carolina. It is worth pointing out that among the Mesozoic basins in North Carolina, the Deep River basin (composed of subbasins 1, 2, and 3 in figure 4) has the lowest average yield, and the Danville basin (basin 5 in figure 4) has the highest. The sedimentary rocks in the Deep River basin are dominated by claystones, siltstones, and other fine-grained sedimentary rocks that produce low yields to wells. Sandstones are limited in thickness and extent. The Danville basin, however, contains sandstone units that locally produce higher yields to wells than the metamorphic rocks outside the basin.

GROUND-WATER QUALITY

Ground-water quality in the crystalline-rock terranes of the Blue Ridge and Piedmont Provinces generally is suitable for drinking and most other purposes. Mineral composition of the regolith and bedrock strongly affects ground-water quality. Water from most light-colored, felsic metamorphic and igneous rocks is soft (hardness less than 60 milligrams per liter [mg/L], as $CaCO_3$), slightly acidic (pH less than 7.0), and contains low concentrations of dissolved solids (Powell and Abe, 1985). Water moving through these silica-rich rocks remains relatively low in dissolved solids because of the chemically resistant nature of the silicate minerals. Water from the dark-colored, mafic metamorphic and igneous rocks generally is hard and somewhat alkaline (pH greater than 7.0) and contains moderate concentrations of dissolved solids as a result of the solubility of calcium- and magnesium-bearing minerals in these rocks. Corrosion of pipes and plumbing fixtures and relatively high concentrations of iron and manganese are the most common water-quality problems.

Water from wells in the sedimentary rocks in the Mesozoic basins generally is hard (hardness greater than 120 mg/L, as $CaCO_3$) to very hard (hardness greater than 180 mg/L, as $CaCO_3$), somewhat alkaline, and contains moderate concentrations of dissolved solids. High concentrations of sulfate (greater than 250 mg/L) are a common problem with water from deep wells and directly correspond to high concentrations of dissolved solids. As in crystalline rocks, ground water in sedimentary rocks locally contains elevated concentrations of iron and manganese. Concentrations of dissolved solids and sulfate tend to increase with well depth (Swain and others, 1991).

The depth of effective circulation of water in the early Mesozoic basins is not known, but depth to the base of potable water appears to be between 1,000 and 2,000 ft in the northern basins (Wood and Wood, 1982) and shallower southward in Virginia and North Carolina. Few chemical data are available for water from deep aquifers. Most water samples have been taken from discharge points at the tops of wells and represent mixtures of water from all contributing aquifers. Water type (Piper, 1944) is variable with depth. Although calcium-magnesium-sodium-bicarbonate type water is common at shallow depths, a calcium-magnesium-sodium-sulfate type or calcium-sulfate type is found at moderate depths, and a sodium-chloride type is found in deep aquifers (Swain and others, 1991; Briel, 1997).

In the early Mesozoic basins, concentrations of the major cations and anions in potable water differ regionally (Wood and Wood, 1982). The calcium-magnesium-bicarbonate-sulfate facies dominates in basins north of Culpeper, Va., except in Maryland, where the calcium-bicarbonate facies dominates. In North Carolina, sulfate generally is absent, and water mostly is a sodium-calcium-magnesium-bicarbonate type and rarely is a calcium-chloride type. Sodium-chloride type waters apparently dominate at depth in all basins in eastern North America. Regional differences in water chemistry may reflect regional differences in aquifer composition and ground-water residence times.

Ambient inorganic ground-water quality for the APRASA study area was evaluated by Briel (1997). Selected statistics computed from chemical analyses of 18,008 ground-water samples (excluding spring-water samples) are presented in table 7. These data were compiled from 10,564 ground-water-quality sites in 11 eastern States (New Jersey, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, Tennessee, North Carolina, South Carolina, Georgia, and Alabama). Briel's (1997) database included 4,173 analyses from 2,682 wells in North Carolina, or 25.4 percent of the ground-water sites and 23.2 percent of the ground-water analyses identified in the APRASA study area.

The range in ground-water quality throughout the Blue Ridge and Piedmont is apparent in the data. As an example, the range in specific conductance (table 7) between the 5th and 95th percentile is more than twice the mean and nearly four times the median (50th percentile) value. This indicates that regional data from an inorganic water-quality investigation cannot be applied with confidence to estimate water quality at any one individual site in North Carolina.

Although political subdivisions generally are of little hydrologic significance, water-resources investigations commonly are delimited by county boundaries; thus, counties provide a usable grid for describing geographic variations in water quality (Briel, 1997). The geographic variation identified by county for total dissolved solids and nitrite plus nitrate (fig. 17) are examples based on Briel's (1997) data. Similar maps can be generated for the remaining constituents shown in table 7.

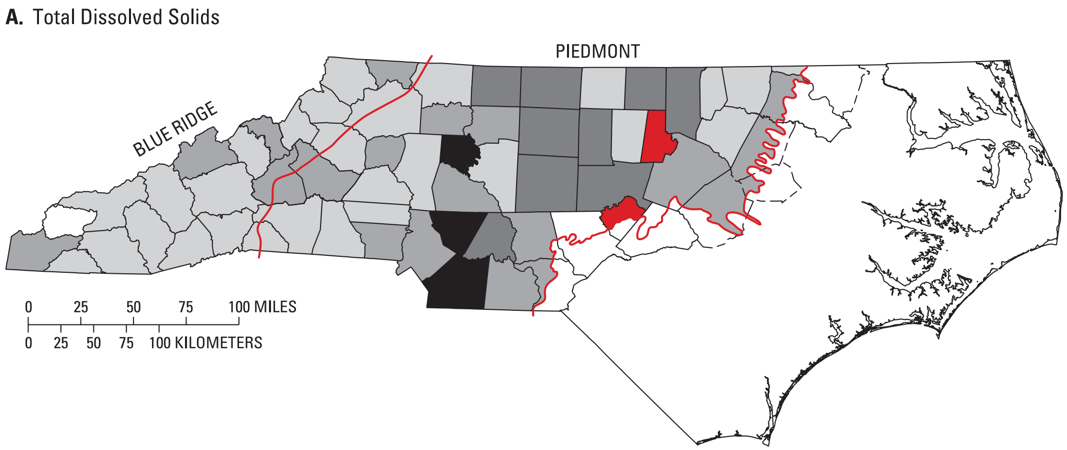
Since Briel (1997) compiled his database, additional ground-water-quality data have become available in North Carolina as a result of two recent studies. Cunningham and Daniel (2001) reported chemical analyses from 51 wells in Orange County. Analytes consisted of common cations and anions, metals and trace elements, nutrients, organic compounds, and radon. Samples also were screened for the presence of fuel compounds and pesticides by using immunoassay techniques. Dissolved oxygen, pH, temperature, specific conductance, and alkalinity were measured in the field. A similar sampling and analysis of water from 70 wells was conducted in Guilford County during 1996–97 (Ragland and others, 1997). A detailed description of dissolved radon measurements and the distribution of radon activities in Guilford County were reported by Spruill and others (1997). In Guilford and Orange Counties, median radon activities in ground-water samples are highest in felsic rocks and lowest in mafic rocks (Spruill and others, 1997; Cunningham and Daniel, 2001). Radon activities in ground water from some hydrogeologic units are as much as 20 times higher than the criterion level of 300 picocuries per liter (pCi/L) proposed by the U.S. Environmental Protection Agency (1999).

Another large and potentially informative database was compiled by the U.S. Department of Energy for the National Uranium Resource Evaluation (NURE) program. Samples were collected and analyzed during 1975–79. By the end of the NURE program, ground-water sampling of the entire State was completed at a reconnaissance scale. The NURE database contains analyses for 5,778 ground-water sampling sites in North Carolina, along with latitude-longitude coordinates of the sampling sites. Using these coordinates, the data can be subdivided by county or physiographic province for further analyses similar to those performed by Briel (1997). The NURE ground-water samples were analyzed by neutron activation analyses for uranium, bromine, chlorine, fluorine, manganese, sodium, aluminum, vanadium, and dysprosium. The data are presented in a hydrogeochemical atlas compiled by Reid (1993).

Table 7. Selected statistics for selected properties and constituents of ground water in the Blue Ridge and Piedmont Provinces, Appalachian Valleys-Piedmont Regional Aquifer-System Analysis (APRASA) study area

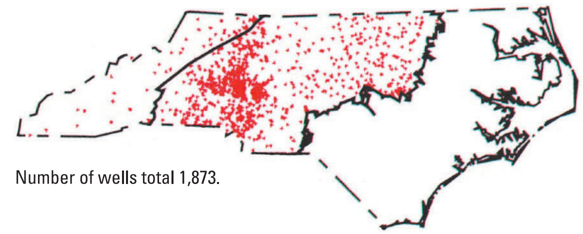
[From Briel (1997; table 5); µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter]

Property or constituent and unit	Blue Ridge					Piedmont				
	Number of analyses	Mean	Percentile values calculated from the data			Number of analyses	Mean	Percentile values calculated from the data		
			5th	50th	95th			5th	50th	95th
Specific conductance, µS/cm at 25 °C	454	154	29	103	440		387	41	280	976
Dissolved solids, residue on evaporation at 180 °C, mg/L	393	94	23	73	220	5,551	227	37	159	554
pH, standard units	416	6.6	5.6	6.6	7.9		6.7	5.2	6.7	8.0
Water temperature, °C	327	13.4	9.7	13.0	18.5	6,991	14.5	10.7	14.0	19.9
Dissolved oxygen, mg/L	14	5.8	.9	6.2	8.2		4.4	.2	4.1	9.8
Calcium, mg/L	442	14	1.2	8.3	42	5,098	38	2.2	25	100
Magnesium, mg/L	477	3.8	.4	2.5	12		14	.7	6.6	36
Sodium, mg/L	441	7.1	1.4	5	17	5,888	27	2	9.5	62
Potassium, mg/L	411	3.3	.3	1.2	3.8		2.5	.4	1.4	6.1
Bicarbonate, mg/L	349	43	6	32	121	4,589	89	6	60	247
Alkalinity, mg/L as $CaCO_3$	322	45	7	32	137		87	5	57	240
Carbonate hardness, mg/L as $CaCO_3$	479	48	6	29	124	8,268	120	8	65	357
Sulfate, mg/L	471	7.7	.3	5	25		35	.8	13	110
Chloride, mg/L	558	6.4	.7	2.1	29	8,739	25	1.1	7	88
Fluoride, mg/L	290	.19	.1	.1	.4		.22	.1	.1	.5
Dissolved silica, mg/L	443	18	5.8	16	35	5,838	19	5	17	37
Nitrite plus nitrate, total, mg/L as N	236	1.1	.01	.2	4.7		4.9	.05	.99	20
Ammonia, total, mg/L as N	106	.03	.01	.05	.05	1,096	1.4	.01	.05	.57
Phosphorus, dissolved, mg/L as P	15	.05	.02	.03	.14		.32	.01	.03	.24
Phosphorus, total, mg /L as P	134	.06	.01	.05	.16	2,115	.20	.01	.05	.45
Iron, dissolved, µg/L	150	228	4	31	1,079		855	4	50	3,201
Iron, total, µg/L	284	443	12	100	1,637	3,109	3,805	17	200	12,000
Manganese, dissolved, µg/L	59	62	1	17	400		429	2	38	1,400
Manganese, total, µg/L	168	254	.15	50	256	2,175	1,000	.10	50	3,958



EXPLANATION

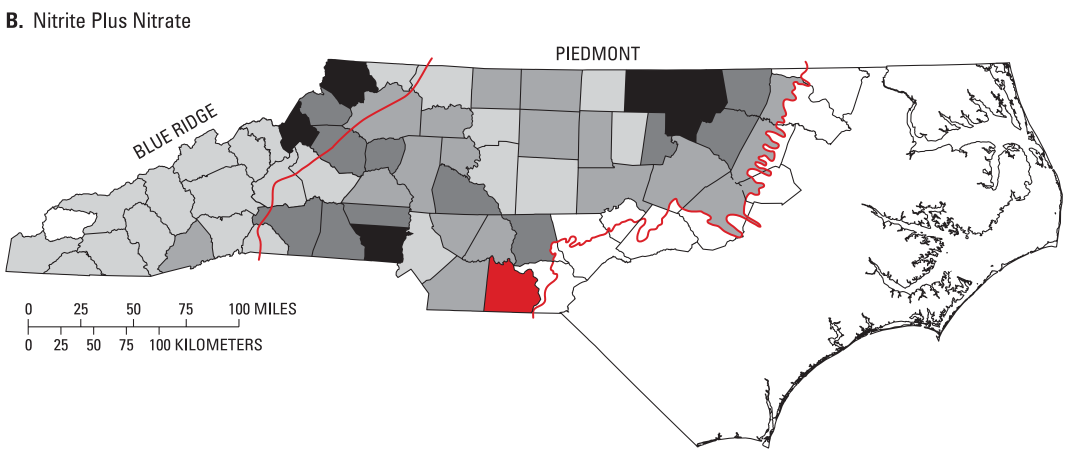
Locations of wells where total dissolved solids concentration has been measured.



Number of wells total 1,873.

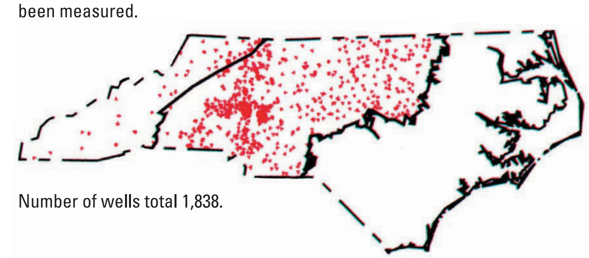
Concentration of dissolved solids, in milligrams per liter. Data available for 59 counties in the study area.

- No data available
- 20 to 81
- 82 to 120
- 121 to 198
- 199 to 307
- 308 to 354
- 355 to 741
- PHYSIOGRAPHIC PROVINCE BOUNDARY



EXPLANATION

Locations of wells where nitrite plus nitrate concentration has been measured.



Number of wells total 1,838.

Concentration of nitrite plus nitrate, in milligrams per liter. Data available for 60 counties in the study area.

- No data available
- 0.01 to 0.28
- 0.29 to 0.74
- 0.75 to 1.35
- 1.36 to 2.87
- 2.88 to 8.77
- 8.78 to 10.0
- PHYSIOGRAPHIC PROVINCE BOUNDARY

Figure 17. Geographic variation of median concentrations of (D) total dissolved solids and (E) nitrite plus nitrate in ground water, by county, in North Carolina (modified from Briel, 1997).

Limited data are available for organic compounds and microbiological pathogens in ground water. Wade and others (1997) investigated pesticide concentrations in 152 wells statewide, with about two-thirds of these wells located in the Coastal Plain. Numerous site-specific, and often contaminant-specific, investigations have been completed under various regulatory programs across the State. This information has not been compiled for a number of reasons. Total coliform bacteria measurements are collected routinely from public water-supply wells. However, there is increased concern regarding ground-water transport of viruses, particularly in situations where ground-water supplies are "under the influence of surface water." As stated in North Carolina regulations, a supply under the influence of surface water is a supply source less than 50 ft from a surface-water body. A recent USGS-sponsored investigation (G. Patterson, U.S. Geological Survey, written commun., June 1999) determined a correlation between stomach ulcers and *Helicobacter pylori* in well water. Microbiological contaminants are an emerging issue for both ground-water and surface-water supplies.

The extensive ground-water-quality data available from Reid (1993), Briel (1997), Spruill and others (1997), and Cunningham and Daniel (2001) can be compiled and analyzed on a county-by-county basis. As the Blue Ridge and Piedmont ground-water study proceeds, the water-quality database will expand as samples are collected and analyzed at the type-area study sites. The work by Briel (1997) provides examples upon which analyses of ground-water-quality data from North Carolina can be modeled.

STATE GROUND-WATER ISSUES AND PROBLEMS

The diversity of ground-water flow conditions in the Blue Ridge and Piedmont Provinces accounts for the complexity and variety of ground-water issues and problems that exist within the study area. Management of ground-water supplies can be difficult because the most permeable parts of the regolith-bedrock aquifer system typically are shallow and unconfined and, therefore, vulnerable to contamination from numerous human activities at land surface. In addition, the aquifers commonly are hydraulically connected to streams and lakes, and contamination of the aquifers in the interstream areas may eventually lead to contamination of surface-water bodies.

Problems related to ground-water development and protection within the Blue Ridge and Piedmont fall into two general categories—(1) ground-water availability and (2) ground-water quality. Well yields are highly variable, even from wells tapping the same hydrogeologic units. Increasing population growth, industrial development, and recent droughts have increased the demand for additional water supplies in the study area. Increased ground-water pumpage has caused declines in water levels in places, decreases in well yields, and interference between cones of depression associated with closely spaced pumping wells. Pumping of wells can induce infiltration from streams or reduce ground-water discharge to streams, thus reducing streamflow by an unacceptable amount (Wood and others, 1972).

The sustainable yield of aquifers in the Blue Ridge and Piedmont Provinces can be difficult to determine. Although the porosity of the regolith can be sufficient to store large quantities of water, it is difficult to determine whether the water in storage is available to supply bedrock wells during periods of limited recharge such as droughts. Data are not readily available to estimate aquifer boundaries and storage coefficients; both types of information are needed to determine the volume of water in storage. (See figure 11 and the related discussion in the section, "Ground-Water Storage.") Recharge areas are not easily defined, which can contribute to the difficulty of protecting bedrock supply wells from contamination.

Water-quality problems result from natural geochemical processes as well as human activities. The mineral composition of rocks can be reflected in the chemical composition of ground water as weathering and dissolution release soluble components. Objection-able concentrations of iron and manganese often occur in water from wells completed in mafic igneous and metaigneous rocks. Hydrogen sulfide often is present in water from slates, shales, and other rocks containing disseminated sulfide minerals. Hardness may reach objectionable levels in water from rocks containing carbonates or other calcium-magnesium-bearing minerals. Other water-quality problems related to natural geochemical processes result from the duration of water-rock contact, seasonal variations in recharge (and accompanying changes in the water table), and the presence of trace metals, radon, radium, and uranium in the rocks and soils.

Nearly all substances are soluble to some extent in water. The density of a liquid also affects its underground movement. Substances less dense than water tend to accumulate at the top of the saturated zone; like petroleum, if a substance is relatively immiscible, it will tend to spread in all directions as a thin layer. Substances denser than water, such as brines and some chlorinated solvents, tend to move downward through the saturated zone to areas where their movement becomes restricted due to a decrease in the size and number of interconnected openings in the regolith or underlying bedrock.

Of all the natural constituents in ground water, radionuclides potentially pose the greatest threat to human health in the Blue Ridge and Piedmont Provinces. Since 1984, indoor radon gas has gained national attention as a major cause of lung cancer in the United States (U.S. Environmental Protection Agency, 1992; National Cancer Institute, 1997). High concentrations of radium and uranium in drinking water are known to be carcinogenic (Gabler and others, 1988; U.S. Environmental Protection Agency, 1994). The crystalline rocks of the Piedmont consist, in part, of granite, granitic gneiss, and other felsic rocks that contain small to moderate amounts of uranium, which, through the process of radioactive decay, is a source of radon gas. The amounts of uranium are sufficient for radon to emanate from the regolith and the part of the underlying fractured rock above the water table (LeGrand, 1987). One of the pathways for radon gas migration into households is through ground water and aeration of the water at faucets and showerheads. In addition to radon, high concentrations of dissolved radium and uranium nuclides have been detected in a few locations in ground-water supplies tapping crystalline and sedimentary rocks of the Piedmont (Zapecza and Szabo, 1988). Recent studies have identified high radon activities in ground water in Guilford and Orange Counties in the central and eastern Piedmont of North Carolina (Spruill and others, 1997; Cunningham and Daniel, 2001).

Many ground-water-quality problems are the result of human activities, including the disposal of wastes onto the land surface, into shallow excavations and septic tanks, or through deep wells, mines, or sinkholes in areas underlain by limestone (karst topography). Ground-water quality also can be degraded by the use of fertilizers and other agricultural chemicals; leaks in sewers, storage tanks, and pipelines; and wastes in animal feedlots. The magnitude of a water-quality problem depends on the size of the area affected and the amount and concentration of the constituent involved, as well as its solubility and density. Affected areas can range in size from point sources, such as septic tanks, to large urban areas having leaky sewer systems and numerous municipal and industrial waste-disposal sites.

Potential water-quality problems related to human activity include:

- discharge from septic tanks;
- petroleum products leaking from storage tanks;
- improper handling and(or) transport of industrial chemicals;
- improperly constructed water-supply wells;
- agricultural activities (application of pesticides and fertilizers, feedlot and barnyard wastes, and leakage from fuel-storage tanks);
- highway de-icing salts; and
- infiltration of contaminated surface water from lakes and streams as a result of nearby pumping from wells.

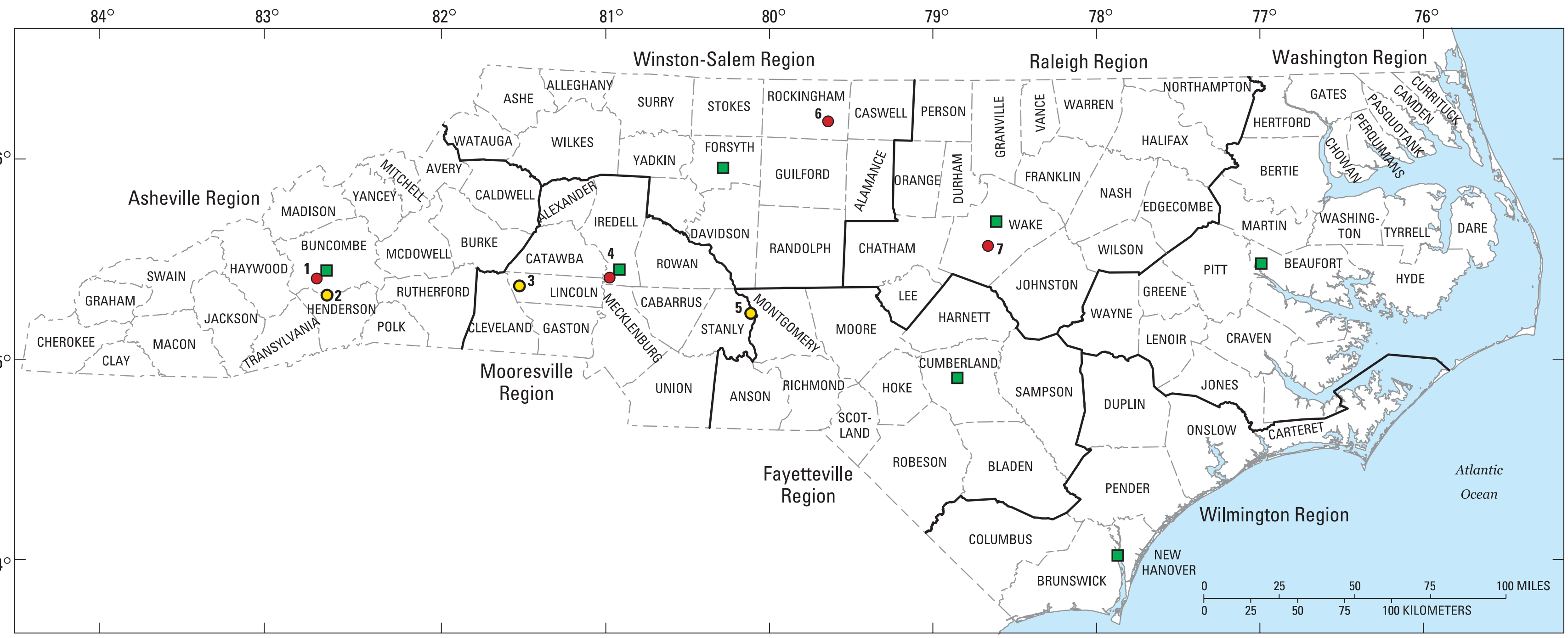
This list does not include all water-quality problems that can result from human activity, but it is representative of some of the most important problems that have been identified in the Blue Ridge and Piedmont Provinces of North Carolina.

The NCDENR Division of Water Quality (DWQ) Groundwater Section is divided into seven geographic regions within the State (fig. 18). Because of their location in the Blue Ridge and Piedmont, four of these regions are involved in this study—the Asheville, Mooresville, Winston-Salem, and Raleigh Regions. Although there are ground-water-related issues and problems that are common to all regions, some issues and problems are more important in individual regions than in others. A few of these issues are described below.

Ground-water concerns in the Asheville Region are many and varied. This region has large land areas previously used for agricultural purposes, such as orchards and Christmas tree farms, that rapidly are being developed for residential use. Issues regarding past pesticide use and its effect on shallow soils and ground water are a growing concern in these areas. Additional concerns include source identification, fate, and transport of chlorinated solvents detected in water-supply wells tapping fractured bedrock aquifers, particularly in areas that are heavily dependent on ground water. Water-quality issues, such as radon, trace metals, and acidity, are naturally occurring and are associated with specific rock formations and lithologies in the region.

On average, more than 64 percent of the population in the 19-county Asheville Region is dependent on ground water as the sole source of drinking water; in 8 of these counties, 75 percent of the population relies on ground water as the only source of potable water. Growth-oriented issues, such as water availability, sustained growth, and water quality, will continue to be concerns in the Asheville Region as North Carolina continues to develop.

Citizens in the Mooresville Region increasingly inquire about ground-water quality, particularly around the lakes (for example, Lake Norman), which are attracting residential development. Other concerns for this region include fate and transport of chlorinated solvents in the bedrock and the effects of poor well



EXPLANATION

MAP NO.		ACTIVE AND POTENTIAL STUDY SITES
1	Bent Creek Demonstration Forest	NCDENR Regional Office
2	NCSU Mountain Horticultural Crops Research Station	4 Active study site (September 2001) and number
3	Indian Creek Basin	3 Potential study site and number
4	Langtree Peninsula at Lake Norman	NCDENR Region boundary
5	Morrow Mountain State Park	
6	NCSU Upper Piedmont Agricultural Research Station	
7	National Training Center for Land-Based Technology and Watershed Protection (Located at NCSU Lake Wheeler Field Research Laboratory)	

Figure 18. Locations of active and potential study sites in the Asheville, Mooresville, Winston-Salem, and Raleigh Regions of the North Carolina Department of Environment and Natural Resources.

construction. Ground-water availability also is a concern because of recent droughts.

In the Winston-Salem Region, chlorinated solvents, petroleum, and nutrients are the predominant ground-water contaminants. Past and present agricultural activities also contribute to ground-water contamination in this region. Other issues in the region include proper well construction and abandonment and possible contamination from nondischarge facilities.

Chlorinated solvents and nutrients are the most common ground-water contaminants in the Raleigh Region. Agricultural products, such as ethylene dibromide, Lasso®, and other pesticides, have been detected in water from wells. Like the Mooresville Region, growth-oriented issues are at the forefront of citizens' concerns. This includes not only the quality, but also the quantity and availability of ground water.

Available Ground-Water Data

Groundwater Section regional staff in Asheville, Mooresville, Winston-Salem, and Raleigh primarily are responsible for reviewing applications for nondischarge permits (nondischarge wastewater disposal systems do not discharge wastewater to surface waters; rather, the discharge is applied either onto the land surface or into the subsurface) and National Pollutant Discharge Elimination System (NPDES) permits. Groundwater Section staff also are responsible for monitoring ground-water contamination incidents from sources other than underground storage tanks (USTs). Regional offices store paper files for each ground-water contamination incident, including comprehensive site assessments and corrective action plans, soil and water sample data, well records, and ground-water-level data. Incident locations and other site information are stored in digital databases at each regional office, as well as in a compiled database at the central office in Raleigh. The databases are available for downloading from the Internet, and an interactive Internet-based ground-water incident database is being tested.

The NCDENR Division of Waste Management (DWM) is responsible for regulating the State's UST program, which includes responding to reports of leaking USTs. Much of the same data collected for non-UST ground-water incidents also is collected by the DWM for UST incidents.

The NCDENR Division of Environmental Health (DEH) regional staff monitor public water supplies in North Carolina. Water-quality and well-construction data are available for all public water-supply wells; some data are in digital format, and some are paper documents.

Well drillers are required to submit Groundwater Section GW-1 forms that contain boring logs, information on well construction, well yield, depth to ground water, and hand-drawn maps of well locations. These forms are required for all wells drilled in the State. Paper copies of these forms are filed in the NCDENR regional offices and the Central Office in Raleigh. The Central Office staff scan and store these forms as digital images; however, the regional offices still rely on paper documents.

Another responsibility of the regional Groundwater Section staff is to monitor compliance of nondischarge permits. Results of ground-water sampling, when required by these permits, are forwarded by the permittees to the NCDENR regional offices and the Central Office in Raleigh. Central Office staff have entered much of these data into digital databases that can be queried, but regional staff continue to rely on paper documents. In cases where ground-water sampling and analysis are required, the sampling interval typically is three times per year, and targeted analytes vary depending on the type of facility being permitted. In addition to the data described above, each region also has unique data sets and ground-water issues as noted below.

Asheville Region

Considerable data are available regarding ground-water quality, availability, and hydrogeologic conditions in the Asheville Region. More than 100,000 individual water wells are on record for the region. Water-level data have been collected from 70 monitoring wells in the region since 1965. In addition, ambient water quality was measured and recorded in 25 to 40 wells from 1974 to 1987. Geophysical logs and pumping test data also are available for many of these wells and for some privately owned wells. The Asheville Region has digitally plotted more than 2,000 public water-supply, monitoring, and observation wells and more than 1,600 UST sites where spills or leaks have occurred. The ground-water incident sites have been mapped by converting digital site-location databases into geographic information system (GIS) compatible files. Ground-water resources in the region also are described in reports by LeGrand and Mundorff (1952), Marsh and Laney (1966), Sumsion and Laney (1967), Dodson and Laney (1968), and Trapp (1970).

The USGS has digital records of 752 water-supply wells (as of February 1, 2002) in the Ground-Water Site Inventory (GWSI) database for this region. Well data also are kept on file in the USGS District Office in Raleigh. The USGS maintains seven continuous-record observation wells in the region, as well as a number of continuous-record streamgaging stations.

The North Carolina Geologic Survey has mapped parts of this region at 1:12,000 scale. The geology also has been mapped by the USGS at a scale of 1:250,000 (Hadley and Nelson, 1971; Rankin and others, 1972; Goldsmith and others, 1988).

Mooresville Region

Every well sampled for chemical analysis in the Mooresville Region has been located and marked on USGS 7.5-minute topographic quadrangles. Most of the sampling events and analytical results also have been recorded in a digital database and stored at the regional office.

Geology in the region has been mapped at 1:250,000 scale by the USGS (Goldsmith and others, 1988), and two publications available in the regional office describe lithology and ground-water chemistry in Iredell County (Peace, 1965; Groves, 1978). Ground-water resources in the region also are described in reports by LeGrand and Mundorff (1952), LeGrand (1954), and Floyd (1965).

The USGS has digital records of 2,055 water-supply wells (as of February 1, 2002) in the GWSI database for this region. Well data also are kept on file in the USGS District Office in Raleigh. The USGS maintains two continuous-record observation wells in the region.

Mecklenburg County, which lies in the south-central part of the Mooresville Region, has developed an ambient well network from which water-level measurements and water-quality data have been collected for 28 wells. This information is available from the Mecklenburg County Department of Environmental Protection (Henry M. Sutton, Mecklenburg County Department of Environmental Protection, oral commun., 2000).

Winston-Salem Region

Winston-Salem Region staff of the Groundwater Section monitored a water-level network composed of 23 unused supply wells from 1974 to 1991, some of which were instrumented with continuous-paper hydrograph recorders. Some of these hydrographs are stored in the region. Water-quality data also were collected into the late 1980's from a separate network of 30 wells. The USGS maintains two long-term observation wells equipped with continuous water-level recorders in the region. The USGS has digital records of 2,194 water-supply wells (as of February 1, 2002) in the GWSI database for this region. Additional well records and well data are kept on file in the USGS District Office in Raleigh.

Geology in this region is described in several maps at different scales. The western part of the region is covered by two maps at a scale of 1:250,000 (Rankin and others, 1972; Espenshade and others, 1975). Geology in the eastern half of the region is mapped at a scale of 1:125,000 (Carpenter, 1982). The southern part of the region in Davidson and Randolph Counties has been mapped at scales ranging from 1:48,000 to 1:62,500 (Stromquist and others, 1971; Stromquist and Sundelius, 1975; Seiders, 1981). Numerous publications are available that describe the geology and ground-water resources of the region, including reports by Mundorff (1948), LeGrand (1954), Bain (1966), Sumsion and Laney (1967), Peace and Link (1971), and Daniel and Sharpless (1983).

Raleigh Region

In addition to the typical data stored by all regional offices, the Raleigh Region has several continuous-paper hydrographs from selected wells. The USGS also has an observation well at Chapel Hill with water-level records covering the period from 1938 to present.

The USGS has digital records of 2,834 water-supply wells (as of February 1, 2002) in the GWSI database for this region. Well data also are kept on file in the USGS District Office in Raleigh. Note that wells in the eastern counties of the Raleigh Region that lie along the Fall Line (fig. 1) often tap bedrock beneath Coastal Plain sediment.

Geology in the region is described in several 1:250,000-scale maps (Wilson, 1979; Wilson and Spence, 1979; McDaniel, 1980; Wilson, 1981; Wilson and others, 1981). Ground-water resources in the region are also described in reports by Mundorff (1946), Pusey (1960), Schipf (1961), Bain (1966), and May and Thomas (1968).

Central Office

As described above, most documents stored in the Groundwater Section regional offices also are stored in the Central Office files, and some have been digitized. In addition to the regulatory data, the Central Office also has initiated ground-water studies in the State and is a repository for data generated during these studies. One such study (North Carolina Division of Water Quality, Groundwater Section, 1997; Pippin and Heller, 1998) was performed in the Kings Mountain belt, which lies within the Mooresville Region, where water levels were recorded periodically from 28 wells, and an aquifer test was conducted. Data from this study are stored digitally.

The Central Office staff also conducted studies to measure the effects of pesticides and intensive livestock operations (ILOs) on the State's ground-water resources from 1995 to 1999; some of these sites were located in the Piedmont and Blue Ridge (Wade and others, 1997; North Carolina Division of Water Quality, Groundwater Section, 1998). Water-level and sampling analyses data have been recorded in digital spreadsheets since the study's inception. Boring logs and other site information associated with this study are filed as paper documents.

A comprehensive digital spreadsheet has been compiled for over 900 wells that were used for ambient monitoring throughout the State. Digital water-level and water-quality data are available for a subset of these wells. Locations of these wells have been plotted using GIS software.

Ground-Water Data Deficiencies

Ground-water level, ground-water quality, and lithologic data have been and continue to be collected from selected sites in the Blue Ridge and Piedmont Provinces. Thousands of well-completion reports have been submitted by drillers to State and county agencies. Much of the information that has been gathered in the past, however, is not stored in a form that is readily available for analysis and interpretation. These data need to be reviewed, and data that can be used for this study need to be entered into computerized databases.

A regional characterization of land use, ground-water quality, recharge/discharge relations, soils and hydrogeologic characterization, and ground-water flow is needed in order to appropriately manage the resource. However, detailed, site-specific information also is needed to understand and manage local problems and solutions.

Ambient ground-water-quality monitoring is inadequate in the Blue Ridge and Piedmont, and there is no statewide program to address this deficiency. Currently (2002), there are only 12 long-term ground-water monitoring wells throughout the entire Blue Ridge and Piedmont region in the USGS-NCDENR Division of Water Resources cooperative ground-water-level network (Howe and Breton, 2001). The existing network is not sufficient to address ground-water resource concerns in the region. A program is needed to monitor ambient water quality so that trends can be evaluated. Both water-level and water-quality aspects of an ambient ground-water program are needed to manage and protect the resource.

The concept of a transition zone between regolith and bedrock, and possible variations due to rock texture, needs to be investigated. Research is needed to characterize the transition zone and define its role in the ground-water flow system. Physical controls on flow and transport within this zone also need to be identified and evaluated. If transition zones are identified and determined to be a significant component of the ground-water flow system, then the conceptual flow systems discussed previously may need to be subset based on the texture of the crystalline bedrock and the type of transition zone that is likely to occur—distinct or indistinct. The crystalline bedrock mantled by thick regolith conceptual system would become two conceptual systems: (1) highly foliated bedrock mantled by thick regolith and (2) massive bedrock mantled by thick regolith. Similarly, the crystalline bedrock mantled by thin regolith conceptual system would become two conceptual systems: (1) highly foliated bedrock mantled by thin regolith and (2) massive bedrock mantled by thin regolith.

Site characterization at the local and regional scale often is inadequate because recharge rates and travel times are virtually unknown, as are ground water/surface water interactions in these terranes. Further work is needed to develop methods of surface and(or) subsurface fracture delineation. Geochemical tracers and isotopic studies may be useful tools for flowpath studies and fracture delineation; certainly they would provide insight into the inter-connectivity of fracture networks.

STUDY DESIGN

This program is designed as an ongoing long-term collaborative investigation to improve the level of understanding of the ground-water system in the Blue Ridge and Piedmont of North Carolina. The program will be organized as a joint investigation using the resources of both the USGS and the NCDENR Division of Water Quality Groundwater Section. In particular, hydrogeologists from the Groundwater Section Central Office and four Regional Offices (Asheville, Mooresville, Winston-Salem, and Raleigh) will participate (fig. 18). Drilling equipment and crews will be provided by the Groundwater Section's Kinston Office.

In order to develop a long-term plan for characterization and eventual utilization of ground-water resources in the Blue Ridge and Piedmont of North Carolina, a summary and analysis of existing data and interpretive studies are needed. The evaluation of known hydrogeologic information, data, and interpretive needs presented in this report serves as a basis to develop studies that investigate ground-water quality, flow, transport, and contribution to streamflow throughout the Blue Ridge and Piedmont.

It is not feasible to obtain site-specific information for all areas in the Blue Ridge and Piedmont. A more feasible approach is to select areas of the Blue Ridge and Piedmont that are most representative of a particular area's land use, geology, and hydrology to obtain an understanding of the hydrologic processes in these areas, and transfer the information from these local “type areas” to similar regional hydrogeologic areas. Ideally, the type areas that are chosen will be representative of larger areas of the two provinces and will allow the hydrogeologic characteristics of the terranes to be studied and described in detail.

For the purpose of this study, the term "type area” applies to a 10- to 100-mi^2 area within a hydrogeologic terrane where information is sufficient to develop and test a concept of ground-water flow by using analytical or numerical methods that can be validated by field measurements. Ideally, selected type areas will be representative of the flow system that is present wherever the particular hydrogeologic terrane is present.

In order to study and better understand the hydrogeology and water quality of ground water in the Blue Ridge and Piedmont, type areas will be identified during the first phase of the study in the hydrogeologic terranes characterized by (1) massive or foliated crystalline rocks overlain by thick regolith and (2) massive or foliated crystalline rocks overlain by thin regolith. Type areas may be identified in the areas underlain by sedimentary rocks of Mesozoic age (fig. 4) during a later phase of the study.

The type-area studies will be designed to address the issues and problems described previously. Much of the information needed to address these issues will be generated by this study. Within each NCDENR region, however, available data will be evaluated for inclusion in databases generated by the type-area studies. Identified data deficiencies will be addressed as needed.

As planning and site selection proceed for the type-area studies, specific ground-water issues and data deficiencies can be selectively studied depending on the priorities identified during the selection process. These issues tend to fall into two general categories: (1) hydrogeology of regolith-fractured rock aquifer systems and (2) ground-water quality.

The movement and fate of specific chemicals and classes of chemicals in ground water also are critical issues in the Blue Ridge and Piedmont. If an appropriate site is identified, site-specific research will focus on water-quality issues related to microbial contamination, as well as the role of microbes in natural bioremediation of contaminant plumes. Migration of solvents and volatile organic compounds associated with petroleum-product UST releases are important concerns. Because of large livestock populations in this region, the presence of nutrients, especially nitrate and other nitrogen compounds, are of concern. As discussed above, radon and other radionuclides are common constituents in granite and granitic gneisses (felsic rocks), and can occur in ground water at concentrations that represent a health hazard. Felsic rocks are found throughout the Blue Ridge and Piedmont. Type areas underlain by felsic rocks will provide an opportunity to study the movement of radon and other radionuclides in ground water.

The type-area studies will collect ground-water-level, ground-water-quality, and hydrogeologic data for the purpose of gaining a better understanding of the movement and geochemistry of ground water within the hydrogeologic terranes that occur in these provinces. In order to accomplish the objectives of the study, a primary goal of the cooperative USGS-Groundwater Section study will be to develop standard procedures for the collection and digital storage of data that are generated. At this time, few standardized procedures are available to guide storage and accessibility of the data needed for this research. These data must be collected according to standard scientific guidelines, and the data and analyses based on these data must be readily available in digital form to the scientific and regulatory community, as well as to the general public. As part of this project, guidelines will be developed for the collection and storage of data. Once the data are readily available, they can be used in a broad range of research that addresses ground-water-related issues.

The planned work for this ground-water study has a wide-ranging scope, including basic data collection, routine interpretive work, and applied research. Work will be done jointly by the USGS and the Groundwater Section. The objectives of the study, the approach to be used to meet these objectives, and the selection of potential study sites are discussed in greater detail in the following sections.

Objectives

Objectives for the State’s Groundwater Section Resource Evaluation Program are described in “A Resource Evaluation Program for Ground Water in North Carolina” (North Carolina Division of Water Quality, Groundwater Section, 1999). This document was prepared by the Resource Evaluation Work Group of the Department of Environment and Natural Resources, Division of Water Quality, Groundwater Section, in October 1999. The cooperative study by the USGS and the Groundwater Section that is described in this report is referred to generally as the “Blue Ridge and Piedmont Ground-Water Project” and is a major component of the Groundwater Section's Resource Evaluation Program.

Based on the type-area concept, sites are being selected within the hydrogeologic terranes of the Blue Ridge and Piedmont Provinces so that ground-water conditions throughout the region can be evaluated based on data collection and analyses conducted at type-area study sites. Research to be conducted at each site will be designed to meet a consistent set of objectives. The objectives listed below have been compiled from the Resource Evaluation Program document (North Carolina Division of Water Quality, Groundwater Section, 1999), the U.S. Geological Survey “Proposal for Ground-Water Investigations in the Piedmont and Mountain Region of North Carolina” (W.L. Cunningham, U.S. Geological Survey, written commun., 1999), and discussions among key participants in the study. The objectives of the cooperative study are as follows:

1. Define hydrogeologic terranes and flow systems within the Blue Ridge and Piedmont Provinces;
2. Describe ground-water quality within each hydrogeologic terrane;
3. Determine vulnerabilities of ground water to contamination in each hydrogeologic terrane;
4. Determine the susceptibility of ground water to over use in each hydrogeologic terrane;
5. Quantify the components of ground-water flow systems in representative areas (type areas) within the hydrogeologic terranes;
6. Assess the response of hydrogeologic systems to ground-water development;
7. Determine the effects of lithology, structure, topography and other relevant geologic or geomorphic features on ground-water quality, quantity, and flow;
8. Determine the relation between surface- and ground-water flow systems and their effects on the quality and availability of ground water;
9. Determine the potential effects of various types of land use and surface applications of chemicals, sludges, and other residues on ground-water quality;
10. Identify the hydrologic factors controlling ground-water recharge and discharge;
11. Provide regional estimates of the ground-water budget, including withdrawals, natural discharge, recharge, and aquifer storage;
12. Provide ongoing training and mentoring to Groundwater Section staff in order to upgrade the hydrogeologic skills needed to carry out the State's ground-water protection program;
13. Develop a digital database to aid in planning, developing, and managing ground-water resources in the Piedmont and Blue Ridge physiographic provinces; and
14. Provide outreach and education to the citizens of North Carolina.

A variety of approaches may be used to meet these objectives. Some may be used at all study sites; some may be used selectively at sites where unique approaches are needed or where unique opportunities for research and site characterization are unavailable at other sites. Some approaches planned for this study are discussed in the following section.

Approach

The first year of the investigation was used primarily to evaluate the state of the science in the Blue Ridge and Piedmont Provinces of North Carolina. Project staff compiled and evaluated existing hydrologic data from the Blue Ridge and Piedmont, identified deficiencies in information and(or) data, identified potential type areas for future intensive study, and generated a plan of study for subsequent years of the study. Sources of data evaluated during the first year included the USGS, universities, county governments, well drillers, and NCDENR Divisions of Water Quality, Health, and Water Resources. Hydrologic data pertaining to soils, water quality, hydrogeology, surface water, ground water, precipitation, and the unsaturated zone were identified and cataloged for potential future use. By the end of the first year, drilling, geologic mapping, and other data collection had been initiated at several sites. By design, the scope of work will increase in subsequent years.

Because details of the investigation in future years will be determined during the first year of study, which is in progress, this discussion provides only a general overview of the work to be accomplished over the next 9 years. As the study proceeds, data from the type-area studies, from applied research, and from the sources mentioned above will be verified and entered into the appropriate USGS National Water Information System (NWIS) database. Available GIS data will be identified and compiled. A library of interpretive information from North Carolina and applicable studies from other Appalachian States will be compiled. Areas of the Blue Ridge and Piedmont Provinces that are not well represented based on the data evaluation will be identified.

Following the first year, the work will focus on

- Filling in data and interpretive deficiencies identified during the first year;
- Characterizing individual type areas within the Blue Ridge and Piedmont;
- Installing type-area study sites for the long-term collection of ambient ground-water quality and quantity data;
- Conducting applied research within these complex hydrogeologic environments using
  a. Unsaturated-zone techniques,
  b. Geophysical techniques,
  c. Geochemical techniques,
  d. Flowpath analysis,
  e. Ground-water flow modeling, and
  f. Comprehensive watershed analysis techniques;
- Transferring type-area results to similar hydrogeologic areas;
- Providing outreach and education related to the ongoing work; and
- Providing ongoing training and mentoring to Groundwater Section staff in order to upgrade the hydrogeologic skills needed to carry out the State's ground-water protection program.

To provide uniformity and consistency of research and data collection, a consistent approach will be used at each type-area study site (D.J. Geddes, M.J. Heller, R.E. Bolich, and K.M. Sarver, written commun., 2000). At individual sites, customized approaches based on unique geochemistry and hydrogeology may be necessary or a valuable addition to meet study goals.

An example of common approaches to be used at each site might be

- Surface geophysics,
- Borehole geophysics,
- Geomorphology,
- Structural geology,
- Determination of regolith thickness,
- Well design, and
- Inorganic ground-water geochemistry.

Site-specific approaches might involve studies of

- Transport through the unsaturated zone,
- Soil chemistry,
- Isotope geochemistry,
- Organic chemistry,
- Age dating,
- Microbial contamination,
- Evaluation of interflow, and
- Analysis of quantity and quality of base flow in streams.

Additional details regarding site-selection criteria and approaches to be used to characterize the type areas are given in the following sections. Based on the site-selection criteria and the goals of this study, project staff have begun to identify study sites in type areas. Some of these sites are described in the section, "Active and Potential Type-Area Study Sites."

Site-Selection Criteria

As part of the site-selection process to identify representative type areas for study, certain selection criteria are required to be met at all sites. Additional criteria may be considered at selected sites that will advance the goals of the study to better understand the geochemistry and behavior of ground-water flow systems in the major hydrogeologic terranes of the North Carolina Blue Ridge and Piedmont. The required and optional site-selection criteria are listed below.

Required Criteria for All Sites

The following criteria must be met when selecting any study site for inclusion in this project.

1. Study sites chosen for ground-water research must be representative of a hydrogeologic terrane within the Blue Ridge and Piedmont Provinces. The areas underlain by metamorphosed carbonate rocks in North Carolina are small and insignificant in terms of human population and, therefore, will not be considered separately from other crystalline rocks in this study. The areas underlain by sedimentary rocks in the Mesozoic basins are distinct from the areas underlain by crystalline rocks and represent only 5.1 percent (table 2) of the hydrogeologic units found in the Blue Ridge and Piedmont; furthermore, the sedimentary rocks in the Deep River basin (fig. 4) have the lowest well yields of all Mesozoic basins. For these reasons, the sedimentary rocks will not be evaluated during the first round of site selection. However, the largest of the Mesozoic basins in North Carolina, the Deep River basin (fig. 4), underlies major population centers and supplies ground water to a large and growing rural population in the eastern Piedmont. For this reason, there is interest in identifying a type area in the Deep River basin during a later phase of the study. During the initial phase of site selection, a selected site must fall within one of two terranes defined below:

a. Massive or foliated crystalline rock mantled by thick regolith, or

b. Massive or foliated crystalline rock mantled by thin regolith.

Varying hydrogeology (including yields to wells) and(or) geochemistry within these two terranes may require defining sub terranes.

2. Research stations must be easily accessible during both the installation phase and for on-going monitoring and research. Ideally, a site will not change ownership or land use during the period of research. Staff should be able to access the site during normal business hours.
3. Previous land use should be known.
4. Research at the site must yield data that will aid Groundwater Section staff in providing technical information requested by the citizens of North Carolina.
5. Educational outreach must be provided.

Optional Criteria for Selected Sites

In addition to meeting the required criteria for all sites, additional criteria may be considered for site selection.

1. Previous hydrogeologic investigations have been conducted at the site that can be built upon.
2. The site is being used for land application of sludge, pesticides, or other potential ground-water contaminants.
3. The site has a documented history of contamination.

Site-Characterization Procedures

A standardized approach will be used to characterize all of the study sites. In addition, specialized techniques may be used to describe unique features of a given site. A manual of standard procedures, including well-construction procedures, has been written by a workgroup selected from project staff and will be followed during all phases of work at the sites.

Standard Procedures for All Study Sites

The hydrogeologic characteristics of each study site, including topography, regolith thickness and composition, transition-zone thickness, type of bedrock (including mineralogy and texture), and geologic structure will be determined. The current and historic land use of a site will be documented.

Sites for boreholes will be selected based on topography, location relative to streams and lakes, and local geology. Continuous rock core will be collected at each borehole site using wire-line technology. These cores will be described and stored in continuous sections starting from the surface to a depth to be determined on site by the supervising hydrogeologist. The thickness and depth of the soil, saprolite, and transition zones will be determined from the coring. Coring also will allow scientists to study lithologic and structural characteristics including foliation and fracturing.

Following completion of coring, clusters of observation wells will be constructed at each borehole site. Wells in a cluster will be installed to depths based on hydrogeologic information determined from the coring. Where coring is not necessary or practical, borehole geophysical techniques will be used to determine subsurface lithology and structure, as well as depth and orientation of fractures.

A minimum of three wells will be installed in each well cluster. The three wells will be screened at different depths to monitor ground-water levels and quality in the saprolite, transition zone, and bedrock. Where it is necessary to determine water-table elevations or locations of ground-water divides for accurate placement of observation wells, a series of 1-in.-diameter wells will be installed in a grid using a truck-mounted Geoprobe® rig where possible. Each well will be surveyed to accurately determine the location and elevation of measuring points for water-level measurements. At sites where benchmarks are available, elevations will be converted to altitude and referenced to the National Geodetic Vertical Datum of 1929.

Specialized Techniques for Selected Study Sites

At selected study sites, specialized investigative techniques may be used in addition to the standard procedures. These techniques include aquifer tests to determine aquifer hydraulic properties, packer testing and sampling of fractures, age dating of ground water, soil chemistry analysis, flowpath analysis, and tracer studies. At sites where age dating, flow-path studies, or ground-water-quality sampling will be performed, wells to be used for aquifer tests or other studies requiring pumping will be at a sufficient distance so that cones of depression (Heath, 1989, p. 30) will not interfere with areas requiring ambient conditions.

Active and Potential Type-Area Study Sites

Using the two categories of hydrogeologic terranes described as (1) crystalline rock mantled by thick regolith and (2) crystalline rock mantled by thin regolith, some potential study sites are listed and briefly described below. The selection criteria described previously make no distinction between sites underlain by massive or foliated bedrock. However, it is important to recognize that the presence or absence of bedrock foliation, particularly if the rock is highly foliated, may influence the character of the transition zone. As the study proceeds and as data become available about the hydraulic characteristics of the transition zone, a subdivision of these crystalline rock categories into two additional categories—massive and weakly foliated, and highly foliated—may be necessary. Objectives for each site are included in each site description, along with other relevant information.

Preparation of this report has occurred at the same time that initial site selections were completed and test drilling and other activities, such as surface geophysical surveys, water-quality sampling, and installation of monitoring equipment, were taking place. Consequently, a brief statement of progress at sites that have already been selected is included, where appropriate, at the end of each site description.

Sites Having Crystalline Rock Mantled by Thick Regolith

Site: Langtree Peninsula at Lake Norman

Location: The site is located in the NCDENR Mooresville Region, Iredell County, N.C. (site 4, fig. 18).

Characteristics: Thick regolith overlies massive, weakly foliated crystalline bedrock of the Charlotte belt. The site is a recreational area located on a peninsula extending into Lake Norman. The property is owned by Davidson College.

Available information includes:

1. Subsurface information from existing well records and well tags.
2. Water-sample analyses from selected wells for volatile organic compounds (VOCs), nutrients, pesticides, herbicides, and bacteria.
3. Conceptual water budget developed by using data from the USGS streamgaging station at Norwood Creek, a similar basin, and the USGS rainfall gaging station at Norman Shores.
4. Changes in land use from 1960 to 1996.
5. A detailed regional geologic map (Goldsmith and others, 1988).
6. Topographic map—Lake Norman North, N.C., 1:24,000-scale, USGS, 7.5-minute series topographic quadrangle.

Objectives for the site:

1. Characterize a typical Charlotte belt hydrogeologic setting.
2. Study the interaction between ground water on a peninsula and surface water in a manmade reservoir (Lake Norman) under natural and pumping conditions.
3. Provide the opportunity for students from nearby universities and colleges to observe site characterization and drilling activities, and to develop projects for senior theses.

Potential partners: Davidson College, The University of North Carolina at Charlotte

Selection criteria met: This site meets all five of the required criteria for site selection. Additionally, this site meets optional criteria 1.

Status: This site has been selected, and extensive work was done at the site during late 2000 and early 2001. Work completed as of September 2001 includes:

1. Continuous rock coring at seven sites.
2. Installation of 30 wells, including six clusters of three wells tapping saprolite, the transition zone, and bedrock.
3. Installation of water-level recorders and satellite telemetry on one cluster of three wells located on the drainage divide.
4. All well sites have been surveyed and referenced to a common datum so that water levels can be compared and the water table beneath part of the site can be mapped.

Site: Indian Creek Basin

Location: The site is located in the NCDENR Mooresville Region, Catawba, Gaston, and Lincoln Counties, N.C. (site 3, fig. 18).

Characteristics: Thick regolith overlies highly foliated and massive crystalline bedrock of the Inner Piedmont belt; foliated bedrock predominates. The primary study area covers 69 mi^2. Land use primarily is rural agricultural; forested land is the second most abundant.

Available information includes:

1. Hydrogeologic conditions, aquifer properties, and recharge rates were characterized to develop a digital ground-water flow model of the area (Daniel and others, 1997).
2. Geochemistry of ground and surface water has been characterized (Daniel and others, 1997).
3. A detailed regional geologic map (Goldsmith and others, 1988).
4. Topographic maps—Banoak, Cherryville, and Lincolnton West, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangles.

Objectives for the site:

1. Refine the existing ground-water flow model to simulate flow beneath narrow valley bottoms and transient conditions, including aquifer response to ground-water withdrawals.
2. Apply new surface and subsurface technology, including surface geophysics, borehole geophysics, and well packers, to further characterize the bedrock aquifer.

Potential partners: None

Selection criteria met: This site meets four of the five required criteria; there currently is no educational outreach component. This criterion would have to be fulfilled. This site meets optional criteria 1.

Status: This site was not selected for the first phase of work.

Site: North Carolina State University Mountain Horticultural Crops Research Station

Location: The site is located in the NCDENR Asheville Region, Henderson County, N.C. (site 2, fig. 18).

Characteristics: Thick (?) regolith overlies fractured bedrock of the Blue Ridge belt. Most of the site is used for orchards. The research station has been in operation since about 1950 and covers 273 acres. The French Broad River flows through the site.

Available information includes:

1. Records of chemical applications and changes in land use may be available because this is an agricultural research site.
2. A regional geologic map (Hadley and Nelson, 1971).
3. Topographic map—Skyland, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangle.

Objectives for the site:

1. Study the fate and transport of agricultural chemicals used for horticulture in ground water.
2. Study the interaction between ground-water flow and flow in a large river (French Broad River).

Potential partners: North Carolina State University (NCSU)

Selection criteria met: This site meets the five required criteria, and optional criteria 2. Results of studies and data will be made available to faculty and students at NCSU.

Status: The site has been selected. Work completed as of September 2001 includes:

1. Reconnaissance of the site and well-site selection.
2. Obtained permission for the drilling of wells.

Site: National Training Center for Land-Based Technology and Watershed Protection

Location: The site is located in the NCDENR Raleigh Region, Wake County, N.C. (site 7, fig. 18).

Characteristics: Thick regolith overlies highly foliated bedrock of the Raleigh belt. The training center occupies over 30 acres at the NCSU Lake Wheeler Field Research Laboratory. Several water-supply wells currently are on the site.

Available information includes:

1. A detailed geologic map by Heller (1996) and a regional geologic map by Wilson and others (1981).
2. Topographic map—Lake Wheeler, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangle.

Objectives for the site:

1. Use the site primarily as a training site for Groundwater Section staff.
2. Provide educational outreach to the legislative and educational community. Outreach is a primary goal for this site.

Potential partners: NCSU College of Agriculture and Life Sciences

Selection criteria met: This site meets all five of the required criteria for site selection and optional criteria 1.

Status: This site has been selected and extensive work was done at the site during late spring and summer 2001. Work completed as of September 2001 includes:

1. Completion of bedrock coring at three sites.
2. Installation of 10 wells in three clusters.
3. Installation of a bedrock production well and two observation wells for use in training methods of conducting aquifer tests and aquifer-test analysis on bedrock wells.
4. Running of borehole geophysical logs.
5. Collection of water-quality samples from one cluster of three wells.
6. Completion of a surface geophysical survey (square array resistivity) at one site to determine bedrock-fracture orientation.

Sites Having Crystalline Rock Mantled by Thin Regolith

Site: Bent Creek Demonstration Forest

Location: The site is located in the NCDENR Asheville Region, Buncombe County, N.C. (site 1, fig. 18).

Characteristics: Thin regolith overlies highly foliated fractured bedrock of the Blue Ridge belt. The demonstration forest occupies about 6,000 acres of the Bent Creek watershed and lies adjacent to Pisgah National Forest. The watershed occupies a breached anticline with the sulfide-rich Ashe Formation exposed at lower elevations along Bent Creek. Water in Bent Creek has low pH and reduced fish populations.

Available information includes:

1. A detailed North Carolina Geological Survey (NCGS) bedrock geologic map (scale 1:12,000) that includes:
    - rock-unit contacts and explanations,
    - structural symbols,
    - cross sections,
    - index metamorphic minerals map,
    - scintillation readings map,
    - stream-sediment heavy minerals, and
    - whole-rock geochemical analyses.
2. Mineral resources summary.
3. Traverse map including station locations.
4. Drainage basin map of heavy mineral occurrences, with the minerals indicated.
5. Petrographic thin sections and section descriptions.
6. Topographic maps—Asheville, Dunsmore Mountain, Enka, and Skyland, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangles.

Objectives for the site:

1. Determine ground-water recharge rates in a pristine mountain environment.
2. Age date ground water.
3. Determine time of travel from recharge to discharge in Bent Creek.
4. Study the relation between ground-water quality and surface-water quality in Bent Creek.
5. Study the effects of ground-water quality on fauna in Bent Creek.
6. Study climatic effects on ground-water resources in the watershed.

Potential partners: N.C. Geological Survey; U.S. Department of Agriculture Forest Service.

Selection criteria met: Access to large areas of the site is limited; all other necessary criteria have been met.

Status: This site has been selected and work was started at the site during the summer of 2001. Work completed as of September 2001 includes:

1. Sites for eight well clusters were selected along Boyd Branch, clearances were obtained, and bedrock core drilling was begun. As of September 2001, core drilling has been completed at six sites.
2. A site was selected for construction of a gaging station on Bent Creek. Permission has been obtained for construction of the gage, and fabrication of the gage is in progress.

Site: Morrow Mountain State Park

Location: The site is located in the NCDENR Mooresville Region, Stanly County, N.C. (site 5, fig. 18).

Characteristics: Thin regolith overlies highly foliated crystalline bedrock (metavolcanic slate and tuff) of the Carolina Slate belt.

Available information includes:

1. Several reports describing the geology of the Morrow Mountain area. The geology is described in a report on the Albemarle quadrangle by Conley (1962) and included in a regional geologic map by Goldsmith and others (1988). More recent 1:24,000-scale mapping of the northern half of the

Morrow Mountain 7.5-minute quadrangle, which includes the park, also is available (Ingram, 1999).

2. Topographic maps—Badin and Morrow Mountain, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangles.

Objectives for the site:

1. Characterize a typical Carolina Slate belt hydrogeologic setting.
2. Provide educational outreach to the citizens of North Carolina by providing a display of the work being done at the research station in the park.

Potential partners: North Carolina Department of Parks and Recreation

Selection criteria met: This site meets all five of the required criteria for site selection. Additionally, this site meets optional criteria 1.

Status: This site was not selected for the first phase of work.

Site: North Carolina State University Upper Piedmont Agricultural Research Station

Location: The site is located in the NCDENR Winston-Salem Region, Rockingham County, N.C. (site 6, fig. 18).

Characteristics: Thin and thick regolith overlie foliated and fractured bedrock of the Milton belt. The research station contains about 670 acres where an ecological trail is being built. The site also hosts a 4-H camp. The research station is used for livestock and agricultural and horticultural (orchard) research.

Available information includes:

1. Agricultural chemical application data.
2. Crop records and changes in land use.
3. Climatological data from three weather stations.
4. Detailed regional geologic map (Carpenter, 1982).
5. Topographic maps—Reidsville and Southeast Eden, N.C., 1:24,000-scale, USGS 7.5-minute series topographic quadrangles.

Objectives for the site:

1. Characterize a typical Milton belt (fig. 7) hydrogeologic setting.
2. Determine effects of agricultural land uses on ground-water quality. Part of the research station is dedicated to livestock research; investigate the possible introduction and movement of nutrients in ground water in this area. Others parts of the research station are used for crop and orchard research; these areas can be studied for the occurrence of pesticides and other chemicals.
3. Study movement of nutrients and other chemicals in the unsaturated and saturated zone.
4. Study effects of ground water on surface-water quality in two bordering streams.
5. Study anisotropic ground-water flow. The structural attitude of bedrock (moderate dip of 30–35 degrees southwest) beneath the research station provides an opportunity to study ground-water movement in the dip direction to the southwest, and oblique to compositional layering and foliation in a northeasterly direction.
6. Provide educational outreach to 4-H camp students and visitors to the research station's ecological walking trail using visual displays.

Potential partners: North Carolina State University

Selection criteria met: This site meets all five of the required criteria for site selection. Additionally, this site meets optional criteria 2.

Status: This site has been selected, and work was started at the site during the late spring and summer of 2001. Work completed as of September 2001 includes:

1. Detailed geologic mapping of the watershed surrounding the site was begun by USGS geologists and Groundwater Section hydrogeologists.
2. A northwest-southeast-trending traverse extending from Carroll Creek to the north to Wolf Island Creek to the south has been proposed, and permission for construction of well clusters along the traverse was obtained.
3. Nine sites for clusters have been identified, and bedrock core drilling has been completed at four sites along the southeastern half of the traverse.

Organization and Federal-State Interaction

The Blue Ridge and Piedmont ground-water study is a major component of the Groundwater Section's statewide Resource Evaluation Program and is designed as an ongoing, long-term collaborative investigation to be conducted jointly by the Groundwater Section and the USGS. Project direction will come from a central staff in Raleigh, North Carolina. This staff will consist of co-project leaders and staff from the Groundwater Section Central Office and the USGS, including hydrologists and hydrogeologists specializing in some combination of database administration, geology, geochemistry, ground- and surface-water interactions, fractured-rock hydrology, and numerical flow simulation.

The study area is divided into four regions based on the NCDENR Regions headquartered in Asheville, Mooresville, Winston-Salem, and Raleigh (fig. 18). One Groundwater Section hydrogeologist will be designated as the Regional Project Manager for each region. These four Regional Project Managers will be responsible for defining the hydrogeologic framework and factors affecting flow in hydrogeologic terranes at study sites within their regions. They will collect and compile data, enter the data into computer files, and provide Central Office staff with descriptions of the hydrogeologic terranes. Further, they will formulate concepts of flow within these terranes and the criteria for selecting type areas for testing these concepts of flow.

The Regional Project Managers will propose suitable type areas and conduct quantitative studies of ground-water flow, quality, and mass transport in the type areas selected and funded by the project. The Regional Project Manager will be responsible for all aspects of the site work, which will be conducted in cooperation with USGS personnel according to a site plan approved by the project staff. Proposed deviations from the site plan will be discussed among project staff until a course of action has been decided. If a course of action cannot be agreed upon, staff will meet to discuss options, and the co-project leaders will determine the suitable option.

Once type areas are selected and research has begun, the USGS North Carolina District of the USGS will pursue additional resources within the USGS, in particular the BRASS (Bedrock Regional Aquifer Systematics Study) Program of the Geologic Discipline and the Toxic Substances Hydrology Program of the Water Resources Discipline. Participation by staff from these programs would enhance the planned work with additional skills in detailed geologic mapping, surface and borehole geophysics, isotope chemistry, and other specialties.

During the spring of 2001, staff from the BRASS Program were invited to participate in work at the NCSU Upper Piedmont Agricultural Research Station in Rockingham County (site 6, fig. 18) by conducting detailed geologic mapping of the watershed surrounding the Research Station. BRASS staff also were asked to prepare geologic maps of the headwaters of the Cullasaja River in Macon County (fig. 1), which is being considered as a study site for comparison with the Bent Creek watershed (site 1, fig. 18). BRASS personnel are currently preparing geologic maps for these two areas.

Proposed Products

Interpretive reports will be published as collaborative efforts between the Groundwater Section and the USGS on various aspects of research at each identified type area. It is anticipated that publications will be prepared for State publication series, USGS publication series, and as articles and abstracts for professional journals and society meetings. Authorship will acknowledge significant contributions by staff from both agencies. Long-term data-collection results will be published on a regular schedule in the USGS annual data report for the North Carolina District.

Data collected during this study also will be stored in the USGS National Water Information System database and in a database to be designed and administered by the Groundwater Section. These data will be available to the general public through the USGS and Groundwater Section Internet sites. Some of these data will be available in real time. Digital data-collection platforms and satellite transmitters will be installed at each study site; at a minimum, one data-collection platform will be installed on one well cluster at each study site to provide continuous information on hydraulic heads in the regolith, transition zone, and bedrock parts of the ground-water system. As one example, a well cluster on the Langtree Peninsula at Lake Norman site has been instrumented (summer of 2001) and data are available on the Internet at http://water.usgs.gov/nc/nwis/current/?type=gw (accessed April 22, 2002). The published reports and GIS coverages produced as part of this study also will be made available on the Internet.

The ultimate product is an increased understanding of the quantity, quality, and distribution of available ground water in the Blue Ridge and Piedmont that can be used by municipal, county, and State planners in developing sustainable and reliable water resources. The emphasis of this ongoing study is long-term protection of water quality in North Carolina.

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